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Petrography and Utilization of Paleozoic, Middle Ordovician Carbonate Rocks in Southern Ontario

By

L. DOLAR-MANTUANI

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Industrial Mineral Report 42

1975

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Parts of this publication may be quoted if credit is given to the Ontario Division of Mines. It is recommended that reference to this report be made in the following form:

Dolar-Mantuani, L.
1975: Petrography and Utilization of Paleozoic, Middle Ordovician Carbonate Rocks in Southern Ontario; Ontario Div. Mines, IMR42, 59 p.

1000-75-HR

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CHART

(back pocket)

Chart A (coloured)—Middle Ordovician Geology of Southern Ontario Showing Carbonate Rock Quarries Sampled for Petrographic Study. Scale 1:1,013,760 or 1 inch to 16 miles.

ABSTRACT

The Middle Ordovician Simcoe Group in southern Ontario consists mainly of limestone and very subordinately of dolostones. Six quarries were studied in detail and samples of rocks were analyzed petrographically and classified according to Folk to determine the four lithologically different Formations, the Gull River, the Bobcaygeon, the Verulam and the Lindsay.

The Gull River Formation was found to have by far the greatest lithological variations. In eastern Ontario around Kingston where the Formation consists of four Members, A, B, C, and D, the dolostones in Member A are interbedded with limestones and are more abundant than the limestones. Farther west around Orillia, the Formation consists of three Members, A, B, and C, and dolostones occur only in one section of Member A. The younger Members which were only examined in one quarry in the west contain more or less pure limestones with the exception of an argillaceous dolomitized limestone at the bottom of Member B. Shaly or clay-rich interbeds and partings are relatively scarce in the Gull River Formation. The limestones are frequently almost pure carbonate rocks, whereas the dolostones are usually argillaceous and may be silty to very fine sandy.

The three younger Formations consist of limestones with shaly interbeds and partings or interbeds of limestones rich in argillaceous material. Many beds are rich in fossils.

Uses in the industry for the quarried material depend to a large extend on the litho-stratigraphic character and on the composition and fabric of the formations occurring in the quarries. The Gull River rocks are generally compact when fresh, especially the limestones. They are used as crushed products but their use as concrete aggregate is somewhat restricted because some beds contain rocks which are alkali-reactive in concrete. Such beds are rare, being confined to two submembers only. The presence of alkali-reactive rocks must be established by special test methods. Petrographic analysis indicates if the rocks in an area or in a quarry are potentially reactive. Alkali reactivity affects the use of the rocks as concrete aggregate only. Special measures must be taken to prevent damage when such material is used in concrete.

High quality rocks occur in sufficiently thick units in the Bobcaygeon Formation to be quarried profitably. The Verulam limestones usually contain many shaly interbeds which do not permit economic development for crushed rock. The low dolomite content makes the limestones suitable for cement production, especially if the Verulam limestones are combined with the overlying Lindsay rocks similar in composition. The intense interbedding or interlamination with clayey beds or laminae makes the Lindsay rocks unsatisfactory for use as crushed concrete aggregate and probably also for many less demanding uses.

Petrography and Utilization of Paleozoic, Middle Ordovician Carbonate Rocks in Southern Ontario

by

L. Dolar-Mantuani[1]

INTRODUCTION

Southern Ontario is part of the West St. Lawrence Lowland's Paleozoic sedimentary region (Bostock 1970, p.27) characterized by northwest-trending belts of carbonate rock separated by belts of predominantly shale. This region, which is south of the Canadian Shield, is largely covered by Pleistocene glacial deposits. Nonetheless, in many places carbonate rocks outcrop, or the overburden is shallow enough to permit economic development of quarries. These carbonate rocks represent one of the most abundant and valuable natural resources in southern Ontario. Ontario is fortunate to have this geological setting because large deposits of carbonate rocks are readily accessible to the most industrialized areas.

The limestones and dolostones occur in three Paleozoic geological Systems, the Ordovician, the Silurian, and the Devonian. Each of these three Systems contains rock varieties suitable for particular industrial uses. High quality rock is quarried for cement, for lime, and for flux stone; but most of the extracted rock is processed to make crushed stone for a variety of special uses such as concrete aggregate, road building, and raw material for the chemical and metallurgical industries. In 1970, Ontario quarries produced about 33 million tons of carbonate rocks. In that year the crushed stone industries used almost three quarters of the production and this, together with the quantities used for cement and lime manufacture, and metallurgical flux accounted for almost 98 percent of the material used (Hewitt and Vos 1972, p.2).

ACKNOWLEDGMENTS

Most of the examinations were done in the Mineral Research Branch Laboratory of the Ontario Division of Mines. Special thanks are due to Mr. D. A. Moddle, Director of the Laboratory, for providing facilities and for the generous assistance of his staff, in particular Mr. R. Laakso for all X-ray examination data and Mr. W. Hicks for the photomicrographs. I wish to thank Mr. D. G. Watt, formerly of the Hydro-Electric Power Commission of Ontario for permission to include thin sections prepared during my employment at Ontario Hydro; Dr. B. A. Liberty, Brock University, for assistance in the stratigraphy and correlation; Messrs D. Harrison and R. Laakso for stimulating discussion of many problems and critical review of the manuscript; Mr. R. H. Howe for reading the manuscript and for his many suggestions;

[1] Petrographer, Ontario Division of Mines. Manuscript approved for publication by Chief, Phanerozoic Geology Section, 3 May, 1973.

Dr. A. L. Punhani for the statistical analysis of the acid-insoluble residues.

My thanks are due to the management and employees of the quarry operators for their permission to sample the quarries and for their assistance in obtaining the samples; to Mr. L. MacDonald, plant chemist at the St. Lawrence Cement Company Limited, Clarkson, for valuable chemical data on Ogden Point limestones.

Support for this research was kindly provided by Dr. D. F. Hewitt, Chief, Phanerozoic Geology Section, Ontario Division of Mines.

PREVIOUS AND RECENT WORK

In view of the widespread use of carbonate rocks in Ontario it is not surprising that much technical and geological data is available for these rocks. The first monograph on carbonate rocks in Ontario with a compilation of their industrial uses by W. G. Miller was published in 1904 (Miller 1904). The properties of the rocks that are important for industry, were first described by W. A. Parks in 1911 (Parks 1912). In 1938, M. F. Goudge increased Park's data considerably in his book "Limestones of Canada, Their Occurrence and Characteristics, Part IV, Ontario" (Goudge 1938). D. F. Hewitt (1960; 1964a) supplied information on the locations and operation of the quarries, and on the processing of the rocks. He gave a general description of the excavated rocks and listed the uses for all carbonate rocks quarried in Ontario. The third edition of "The Limestone Industries in Ontario" by Hewitt and Vos (1972) contains recent data on these rapidly growing and quickly changing industries. Information by Vos (1969) is available on potential quarry locations and the depth of overburden along the Niagara Escarpment where several of the most productive quarries are situated. In "Aggregate Resources of Southern Ontario", Vos (1972) discussed briefly the supply of aggregates in southern Ontario in the context of the geological formations in which they occur. In addition, Hewitt and his co-workers have published a series of reports, each based on a geological map-sheet and covering the practical applications of the carbonate rocks quarried in the area (e.g. Hewitt and Yundt 1971).

APPLICATION OF PETROGRAPHY TO THE INDUSTRIAL USE OF CARBONATE ROCKS

Although a large amount of valuable information about Ontario's carbonate rocks has been written, no systematic description of petrographic characteristics of the quarried material has been published. The present study was undertaken to provide petrographic data on the rocks and to relate the data to industrial uses for the rocks.

Petrography, which is the study of compositional, textural and structural properties of rocks and rock forming minerals, can be applied to determine the fundamental properties which are decisive in establishing the practical uses of natural materials (K. Mather 1953; Dolar-Mantuani 1970a). The basic questions which concern experienced petrographers dealing with industrial rocks and minerals are:

1. Are the rocks suitable for a particular use?
2. What compositional and textural properties affect the quality of the rocks for the intended use?
3. How does the rock deposit compare with other deposits and with other rocks known to be satisfactory for the intended use?
4. Can separation or beneficiation techniques be used to improve the quality of the product?

The answer to any of these and similiar questions must be based on thorough knowledge of the rocks, and familiarity with their properties is essential (Dolar-Mantuani 1970b).

As K. Mather (1953) has pointed out, when considering a rock deposit for a given application, questions concerning production must also be answered such as:

1. Are the rocks available in adequate quantity for the intended use?
2. Are the beds thick enough to permit aggregate of the desired maximum size to be made?
3. Are the rocks strong and cohesive enough to be processed and emerge as a graded product in the size ranges desired?

Petrographic descriptions of Ontario's carbonate rocks can be useful in various ways. They will be valuable to both producers and users when selecting rocks for a given application. The information provided will be useful for anticipating problems with rock qualities in different areas, and in some cases it will indicate the need for beneficiation or other corrective measures. Descriptions of rocks occurring in various formations indicate what rocks will be found if quarries are deepened and reach another geological unit.

This report discusses detailed petrographic examinations of geological formations or members, and the petrographic features of rocks that occur in the selected representative quarries. The geological units which can be recognized in quarry faces serve

as the basis for the petrographic descriptions. The commercially important features are described in general terms for the formations represented in the selected quarries. Both desirable and undesirable features are discussed, and several petrographic methods of assessing the quality of rocks are given.

AREA STUDIED

The oldest Paleozoic carbonate rocks in the West St. Lawrence Lowland that are widely used in industry, belong to the Simcoe Group. This stratigraphic term was introduced by B.A. Liberty (1955, p.143) for rocks of Middle Ordovician age occurring in an area south of the Canadian Shield and west of the Frontenac Axis. Liberty (1963) divided the Simcoe Group into four Formations, the Gull River, Bobcaygeon, Verulam, and Lindsay. This group was selected for the petrographic study of Ontario carbonate rocks, because it is widely used by the industry. Chart A (back pocket) shows the area of the Simcoe Group and the four Formations. The area is bounded on the NE by the Canadian Shield along a line between Midland and Kingston; on the south by Lake Ontario from Kingston to Newcastle; on the SW by the conformably overlying Whitby Formation along a line Newcastle-Lake Scugog-Aurora-Collingwood; and on the NW by Georgian Bay from Collingwood to Midland.

Twenty-four operating quarries are located in this area including two major quarries which each produce over 1,000,000 tons of crushed rock a year. The geological setting of all the operating quarries and some abandoned ones, described by Hewitt (1964a), and by Hewitt and Vos (1972) shows that some quarries are located in single lithostratigraphic units, whereas others extend into a second unit.

SAMPLING

The material examined was collected by the author in 1971 and 1972 from six quarries (shown on Chart A). These six quarries provided samples from two separate quarries for each of the four Formations. Samples were selected mainly from the quarry faces but some were collected from crushed material in the stockpiles. The samples from the quarry faces were taken to represent the main rock varieties being quarried. Shaly interbeds and partings may not be adequately represented because the samples were not taken at regular intervals. There is, however, a tendency to lose shaly material during blasting, crushing, and sieving so the samples are approximately representative of production.

With the exception of acid-insoluble-residue data, the results of the examinations were not evaluated statistically because the number of samples was too small in most cases, but the results were adequate to indicate the lithological trends in the geological units and quarries.

DESCRIPTION OF CARBONATE ROCKS

Rocks are characterized by composition, texture and structure, all of which are dependent on the origin of the rock and subsequent alteration and changes produced by weathering.

COMPOSITION

Sedimentary carbonate rocks consist mainly of two minerals: calcite, which is calcium carbonate ($CaCO_3$) and dolomite, which is calcium-magnesium carbonate ($CaMg(CO_3)_2$). The carbonate rock classification based on these two major constituents is shown in Table 1.

The ratio between calcite and dolomite is commonly obtained by X-ray diffractometry but may also be obtained by wet chemical analysis or other methods (see the section "Methods of Examination").

The term magnesian limestone may be used when magnesium replaces some of the calcium in the mineral calcite and crystals of dolomite are not identifiable (e.g. Pettijohn 1949, p.313). In these cases the percentages of magnesium are usually small. The term dolostone, analogous to limestone

Table 1 | ROCK CLASSIFICATION BASED ON MINERAL AND CHEMICAL COMPOSITION

NAME	CALCITE PERCENT	DOLOMITE PERCENT	MgO [1] PERCENT	CALCITE/DOLOMITE RATIO
Limestone	90 – 100	0 – 10	Below 2.1	Above 9.0
Dolomitic Limestone	50 – 90	10 – 50	2.1 – 10.8	9.0 – 1.0
Calcitic Dolostone	10 – 50	50 – 90	10.8 – 19.5	1.0 – 0.11
Dolostone	0 – 10	90 – 100	19.5 – 21.6	Below 0.11

[1] The MgO limits are only valid for pure carbonate rocks containing no noncarbonate impurities (Hewitt 1960, p.v).

(Shrock 1948, p.126), is being used more and more widely for the rock *dolomite* to distinguish it from the mineral *dolomite*. Dolostone is used in this report.

ORIGIN REFLECTED IN COMPOSITION

The essential features based on origin that distinguish carbonate rocks from other rocks, were summarized by W. E. Ham and L. C. Pray (1962, p.2) as follows:

> They [limestone and dolostone] are set distinctly apart from related rock families by their intrabasinal and highly local origin, their genetic dependence upon organic activity, and their extreme susceptibility to postdepositional modification.

The Paleozoic carbonate rocks in Ontario were formed by deposition, on the bottom of the sea or tidal flats, of predominantly microcrystalline calcium carbonate mud, fragments of penecontemporaneous, generally weakly consolidated carbonate sediments and detritus of organisms. Deposits adjacent to the great mass of the Canadian Shield commonly contain noncarbonate impurities derived from weathered and disintegrated rocks from the Shield. They consist of terrigenous clastic minerals, such as quartz, feldspars, and clay minerals. The most common noncarbonate constituents formed in the location where deposition of carbonate rock occurred, are chert, authigenic crystals of quartz, sulphates and sulphides. There is practically no limit to the variety of detrital and authigenic minerals other than carbonates (Carozzi 1960). Rocks that contain more than 50 percent of terrigenous noncarbonates are classified as sandstone, mudstone, or shale depending on the composition, grain size, and structure of the rock. These rocks frequently occur within assemblages of carbonate rocks, interbedded, interlayered, or interlaminated with carbonate on a scale of a millimeter or less.

Pure carbonate rocks do occur usually in reefs, single beds or sets of a few beds. Some deposits may be more than 100 feet (30.5 m) thick. Diagnetic changes by solution, cementation, later crystalization, and replacement especially with dolomite, may significantly alter the original composition and texture of the rocks.

TEXTURE

Texture refers to the grain-to-grain relationship, to the size, shape, and arrangement of the component particles of a rock (American Geological Institute 1966). The carbonate rocks show great variations in texture. They are coarsely crystalline to aphanocrystalline, and are uniform or heterogeneous in grain size. The shape of the carbonate minerals is usually equant. Calcite grains are commonly anhedral with nearly straight or interlocking boundaries, and dolomite grains are commonly euhedral to subhedral with typical rhombohedral crystal form. The relatively coarse rhombohedra are very prominent if the mineral dolomite occurs in two generations, one of which is coarser grained than the surrounding partially dolomitized calcitic matrix. Authigenic quartz is typically euhedral-prismatic, pyrite is frequently cubic, and gypsum grains are almost always irregular-anhedral. Clastic quartz and feldspar grains are anhedral and angular to rounded. Variations in texture are produced by the presence of various fossils, recrystallization, partial leaching and subsequent filling of openings, and dolomitization with all the intermediate phases and selective replacements. Changes in composition and texture may be sudden or gradual; they may occur in the form of intercalations or of repeated layers and laminae, the last on a microscopic scale. The need for exact textural terminology (Dolar-Mantuani 1951) has increased with increasing industrial use of the rocks, but seems more and more complex as the research on recent carbonate rocks intensifies (Bathurst 1974).

STRUCTURE

The term structure pertains to the larger features of a rock mass, or rock unit representing a discontinuity like bedding and jointing or major inhomogeneity visible in outcrops and quarries (American Geological Institute 1972). The Paleozoic carbonate rocks in Ontario are usually layered, the layers either being horizontal or dipping gently. Reef rocks are rather exceptional in the Simcoe Group. The horizontal layers are more or less evenly bedded but usually differ in thickness in various beds. Single layers may be split in two or three layers on weathered surfaces showing the presence of weakness planes parallel to the layering.

Joints in the Ontario carbonate rocks are mostly vertical or nearly vertical. During or after diagenesis abrupt discontinuities were produced by contraction, tectonic forces, or the removal of pressure as the rocks were uncovered by erosion. Liberty (1971, p.8) believed most faulting to be due to post-ice age adjustment to load, but other mechanisms must be considered for larger faults.

CLASSIFICATION

The adoption of a generally accepted standard classification system with well defined terms is

strongly recommended because it is essential for meaningful comparisons of materials examined by different petrographers. Furthermore, a standard classification will help to establish the harmful rock varieties and to relate specific rocks to industrial performance. The heterogeneity of this rock group, however, makes the development of a uniform, widely applicable classification a formidable task.

The most widely accepted classification is the one developed by R. L. Folk (1959; 1962; 1968) (see Appendix I). It is based on the origin, composition, and texture with texture emphasized by the use of textural building blocks. His terms describe textural details which help to distinguish carbonate rock varieties, and thus have certain industrial significance.

The Paleozoic carbonate rocks of Ontario are often dolomitized and this complicates the application of a uniform classification system. In this study intended for use by the industry, the numerical values used by Folk to differentiate textural varieties, were not always determined. Instead, estimates were used and the rock names were modified by additional descriptive terms. Because of the emphasis on uses for the rocks, fossil identification was omitted as having no immediate industrial significance.

A short summary of Folk's classification, and description of selected petrographic and classification terms are given in Appendix I. For more detail the reader is referred to the original papers and Folk's book on the "Petrology of Sedimentary Rocks" (1968).

METHODS OF EXAMINATION

Laboratory examinations were done by optical petrographic methods following ASTM Designation: C295 using a stereomicroscope for hand specimens[1] and a petrographic microscope for thin sections and powder mounted sections. Over 150 thin sections were prepared from almost all samples taken along the quarry faces. Several hundred thin sections were also obtained for this study from Ontario Hydro where the author was previously employed.

Preliminary separation of limestones and dolostones was made on the basis of differences in acid solubility. Calcite dissolves in acid quickly with vigorous effervescence, while dolomite dissolves slowly with slow effervescence.

The percentages of acid-insoluble residues, the noncarbonate constituents, were determined by dissolving the carbonates in 20 percent hydrochloric acid, and drying and weighing the residue. The percentages of insoluble residues give a rough approximation of the purity of the carbonate rocks. More accurate methods are required for exact determination of the types and amounts of noncarbonate constituents.

The copper nitrate staining test which helps to make a preliminary petrographic evaluation of argillaceous carbonate rocks and shales was frequently used for cursory identification of the composition of the samples (see Appendix III).

The following determinations were made by R. Laakso using the X-ray diffraction method:

Information on the carbonate minerals was obtained by X-ray diffraction analyses of the rocks in the "as received state"; information on the noncarbonate minerals, the nonclay and clay minerals by the analyses of the acid-insoluble (weak) residue. The acid-insoluble residues were sedimented on glass slides and after a general trace for all noncarbonate minerals was run on the diffraction equipment, the slide was heated with an infra-red heat lamp and the lower angles for clay minerals were rerun. If variations in this lower portion of the diffractometry trace were found, they were interpreted to mean that expanding and interlayered clay minerals were present (Bradley and Grim 1961, p.223 and 225; see also determination of clay minerals in Verulam argillaceous limestones described in the section "Mineral Investigation by X-ray Diffractometry" in Dolar-Mantuani and Laakso 1974, p.436).

The dolomite to calcite ratios were determined by the X-ray method, and the percentages of calcite and dolomite were calculated from the results. The calcite to dolomite ratios of the Ontario Hydro samples were determined by several methods: X-ray diffractometry, wet chemical analysis, atomic absorption spectrophotometry and carbon dioxide evolution displacement (Dreimanis 1962). Differences in the calcite to dolomite ratios obtained by different methods, for a given sample, were small (Dolar-Mantuani 1971a, p.1).

BASIC COMPOSITION

The three components, calcite, dolomite, and insoluble residues, were used to represent the basic composition of the rocks. The basic compositions help to classify the carbonate rocks and the lithic variation in a quarry. These three parameters were used to illustrate graphically the uniformity or variability of the composition of the formations and to make a preliminary assessment of their suitability

[1] Colour determinations of hand specimens were made by using Munsell's Rock-Color chart in which the colours are expressed in symbols (Rock-Color Chart Committee 1963).

for various industrial uses. The compositions were plotted on an equilateral triangle with each corner representing 100 percent of one of the three parameters (e.g. Figure 2). The numerical data for each sample can be obtained by referring to the individual points on the graph.

In the formations which consist of more or less unicarbonate rocks, limestones or dolostones, the points tend to concentrate near the calcite/insoluble residue or dolomite/insoluble residue sites of the triangle. To avoid accumulation of many points in a small area, a semilogarithmic graph was plotted using two parameters only. The percentage of insoluble residue was plotted on the ordinate and the percentage of the minor carbonate mineral, dolomite for limestones and calcite for dolostones, was plotted on the abscissa. The complete range of acid-insoluble residues in carbonate rock assemblages, including the argillaceous interbeds, can be plotted by this method. The enlarged scale on the abscissa permits accurate establishment of the degree of dolomitization in limestone or, the amount of calcite remaining or introduced later in a dolostone. If necessary, the third parameter can be obtained by adding the percentages of the two parameters read from the graph and subtracting the sum from 100.

CLASSIFICATION

The rocks are classified according to composition using the calcite to dolomite ratios, the percentages of the acid-insoluble residues, the essential accessory minerals identified by the X-ray method and the analyses of the thin sections. The examination of thin sections is essential for determining the texture, a necessary parameter when following Folk's classification.

STANDARD ACCEPTANCE TESTS

Detailed petrographic examinations do not, however, eliminate the need for applying standard acceptance tests appropriate for a particular use. Several of these tests are mentioned by Hewitt (1960, p.8-16); those applying to concrete materials are described in the specifications of the Canadian Standards Association (1973) and in the appropriate annually revised and updated Books of Standards of the American Society for Testing and Materials. It is necessary to be aware of the principle differences between the results of standard acceptance tests and those obtained from petrographic analysis. The former give average figures obtained on bulk samples, the latter are based on examination, identification and evaluation of single pieces of a sample. An experienced petrographer makes qualitative assessments of rocks by comparing samples with similar rocks of known service performance (Dolar-Mantuani 1966; 1969b; 1970a; 1970b).

The special methods for examination of reactive carbonate rocks are described in Appendix II.

CRUSHED STOCKPILE SAMPLES

Only a few crushed samples from stockpiles were examined. The standard recommended practice given in ASTM Designation: C 295 was followed when examining the processed material. The crushed stockpile samples were sieved through standard sieves, and at least 200 particles of each fraction were identified and evaluated (*see* Dolar-Mantuani 1966, p.9; Dolar-Mantuani and Punhani 1974).

MIDDLE ORDOVICIAN SIMCOE GROUP

The term "Simcoe Group" was proposed by Liberty (1955) for the limestone formations of Trenton-Black River age in southern Ontario. The Group has a thickness of 600 to 750 feet (183 to 228.5 m). It is underlain by the Shadow Lake Formation that consists of up to 40 feet (12.2 m) of basal clastics, mainly calcareous arkose and arenaceous shale (Hewitt and Vos 1972, p.12); it is overlain by the black fissile shale of the Whitby Formation of the Nottawasaga Group.

The Ordovician strata exhibit a gentle regional inclination to the southwest; the dip is only 20 to 30 feet per mile (3.8 to 5.7 m per km), so that strata in individual exposures appear flat lying (Liberty 1969, p.86).

DESCRIPTION OF FORMATIONS

A Formation is the fundamental formal unit of a lithostratigraphic classification (International Subcommission on Stratigraphic Terminology 1972). It is commonly defined as a mappable rock unit that is lithologically distinct from units above and below it and can be recognized on a lithological and (or) chemical basis, largely without recourse to fossils.

Table 2 COMPARISON OF MIDDLE ORDOVICIAN STRATIGRAPHIC NOMENCLATURE
prepared by B. A. Liberty

	B. A. Liberty (1972)		G. M. Kay Composite	D. F. Hewitt (1960)
SIMCOE GROUP	Lindsay Formation	Upper Member 200 ft.	Hillier	Upper Trenton Formation
		Lower Member 100 ft.		
	Verulam Formation 200–350 ft.	Upper Member	Hallowell	Middle Trenton Formation
		Lower Member	Sherman Fall	
	Bobcaygeon Formation 20–60 ft.	Upper Member	Kirkfield	Lower Trenton Formation
		Middle Member	Coboconk	
		Lower Member		Upper Black River Formation
	Gull River Formation 60–350 ft.	Member D	Chaumont	Middle Black River Formation
		Member C	Lowville	
		Member B	Pamelia	Lower Black River Formation
		Member A		
	Shadow Lake Formation up to 40 ft.			Basal Clastics

B. A. Liberty, who during the past 20 years has done the most detailed work on the lithostratigraphy of the Middle Ordovician rocks in southern Ontario, has divided the Simcoe Group into four Formations, the Gull River, the Bobcaygeon, the Verulam, and the Lindsay Formation (Liberty 1969). Their areas of outcrop are shown on Chart A (back pocket). Table 2 is a comparison of stratigraphic nomenclature for the rocks comprising the Simcoe Group. This table compares the present lithostratigraphic nomenclature (first column) with the biostratigraphic nomenclature (second column) and the earlier, Trenton-Black River nomenclature (third column). Hewitt and Vos (1972, Table 21, p.13) used Liberty's (1969) lithostratigraphic subdivision for the Georgian Bay-Lake Ontario area.

Gull River Formation

The Gull River Formation, the oldest formation in the Simcoe Group, occurs in a narrow belt along the Canadian Shield south of the line extending from Midland on Georgian Bay eastward across Lake Couchiching to Kingston. Liberty (1971) divides this Formation into four distinct Members, A, B, C, and D. He further subdivides the lower Members, A and B, into three and two submembers, respectively. The uppermost Member D occurs in the Kingston area only (Liberty 1971, p.4). The subdivision of members demonstrates the great lithological variations occurring in the Gull River Formation. This applies particularly for Member A. This Member is described therefore in greater detail than the other Gull River Members and the other Formations of the Simcoe Group.

REPRESENTATIVE QUARRIES

The two quarries selected to represent the Gull River Formation are the Pittsburg quarry near Kingston and the Uhthoff quarry near Orillia. Both quarries consist of limestones and dolostones and have been worked to about the same depth, 68 to 70 feet (20.7 to 21.3 m), in three lifts in the Pittsburg quarry and in two lifts in the Uhthoff quarry. The Pittsburg quarry is developed entirely in the Gull River Member A, while the Uhthoff quarry is developed in all three members of the Gull River Formation that occur in the west. The Gull River beds in this quarry are topped by a few weathered beds of the Bobcaygeon Formation which are described in the section "Uhthoff Quarry" under "Bobcaygeon Formation."

PREVIOUS WORK

The rocks occurring in quarries of the Gull River Formation were briefly described by Hewitt (1960). Descriptions of the rocks are also found in many papers by Liberty (see "Selected References"). Reports of the Ontario Division of Mines and Memoirs of the Geological Survey of Canada contain geological data applicable to industrial uses. Lists of names of rocks occurring in the Gull River Members are given in recent papers by K. K. Mukherji (1969), R. G. Greggs and M. W. Sargent (1971) and others, each paper dealing with special aspects of this geologically and petrographically interesting formation.

Because the Gull River Formation includes beds that contain alkali-reactive rocks, this Formation is probably the most intensively studied carbonate rock formation in Ontario. Members of the Building Research Division of the National Research Council in Ottawa have made thorough examinations of these rocks which resulted in numerous publications, mainly by E. G. Swenson and J. E. Gillott between 1957 and 1972 (see Appendix II). Their investigations showed that the reactivity might adversely affect concrete when the rocks are used as aggregates. Petrographic and alkali-reactivity studies of 14 locations in the Gull River Formation along the Canadian Shield from Georgian Bay to Kingston were performed by the author (Dolar-Mantuani 1964; 1971a). On the basis of these results Liberty (1971, personal communication) concluded that only two adjacent submembers of the Formation contain reactive beds. Petrographic and detailed mineralogical descriptions of one submember that contains reactive rocks were published by Gillott (1963). Discussions of the reactivity, the subsequent expansion of the rocks, and special precautions recommended for safe inclusion of the rocks as aggregate in concrete, are given in Appendix II.

SAMPLES AND SPECIAL TESTS PERFORMED

The petrographic descriptions of the Gull River rocks are based on examinations of over 80 samples collected for this study from the Pittsburg and Uhthoff quarry faces.

Data obtained in a previous study of 230 samples from the Gull River Formation in Ontario were also used (Dolar-Mantuani 1964; 1971a). These previous samples were examined in thin sections and were tested for expansion due to alkali reactivity by the Rock Cylinder Method (ASTM Designation: C 586) for periods of up to seven years. Absorption and various specific gravities[1] were determined at atmospheric pressure and at 15 mm Hg (Dolar-Mantuani 1969b) on small pieces of more than 30 samples that were studied for reactivity (Dolar-Mantuani 1971a). The amounts of calcite, dolomite, and acid-insoluble residues were determined on 175 Gull River samples. The texture and the mineral constituents were determined in thin sections, and the mineral composition was confirmed by X-ray diffractometry.

The changes in the depths of the lifts in the different parts of the quarries, especially in the Pittsburg quarry, make it difficult to correlate the new set of samples with those taken some 10 years ago. The great variability in rocks occurring in the same bed adds to the difficulty. Most of the petrographic conclusions on the rocks are, therefore, based on the new samples.

GULL RIVER MEMBER A

Pittsburg and Uhthoff Quarries

While all three lifts of the Pittsburg quarry are operated in Member A of the Gull River Formation (Photo 1), only the lower 27-foot (8.2 m) lift of the Uhthoff quarry is operated in this Member (Photo 2).

The beds in both quarries are horizontal, varying in thickness from a few centimetres to more than a metre. In some beds the thickness reflects differences in composition. Thinly bedded rocks are normally rich in argillaceous components but typically shaly interbeds are rare in both quarries.

There are significant differences among the Member A rocks in both quarries. The most significant feature in the Pittsburg quarry is repeated interbedding of units of different thicknesses of light-grey limestone and buff or greenish dolostone, most easily visible on the slightly weathered northern face of the quarry. Several limestone beds in the middle lift of the quarry weather slightly greenish causing the misleading interpretation that they are dolostones. In these beds of alternating greenish-buff and grey limestone, only the degree of dolomitization varies.

Even after a few years of exposure, weathering in quarry faces is usually only a few millimetres deep. However, a deeply weathered bed is visible in the lower part of the northern face of the Pittsburg quarry, consisting of a dark greenish grey, friable

[1] Apparent, bulk saturated surface dry, and oven dry specific gravities; see ASTM Designations: C127 and E12.

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Photo 1–Pittsburg quarry, Gull River Member A; the quarry is about 70 feet (21.3 m) deep and is operated in three lifts; view towards southeast corner of the quarry. Photo by J. Mantuani.

dolostone. The intense weathering of this bed is probably due to the former presence of iron sulphides.

In the Uhthoff quarry the most significant feature of Member A rocks is their mottling. Mottling is most prominent in the limestones which compose the lower two-thirds of the lift but also occurs in several dolostone beds in the upper part of the 9-foot (2.7 m) dolostone unit overlying the limestones (see Figure 1). In the lower limestone beds the mottles are small, 1 to 2 cm in size, and convoluted. In the upper limestone beds the mottles are irregularly banded and larger, averaging about 5 cm in size. The latter unit contains a bed with chert nodules which are whitish to greyish. In cross-section the nodules are shaped like flattened lenses; in the plane parallel to the layering they have an irregular shape. Rarely the chert occurs as interconnected spherical concentrations.

Dolostones of the Uhthoff quarry occur in two distinct varieties: the upper set of dolostones weathers to greenish hues, and the lower set to brownish hues. Special features of the Uhthoff quarry are breccia-like desiccation patterns on the top of one dolostone bed, and narrow calcirudite interbeds which occur at the bottom of the quarry and less prominently at the contact between the Members A and B.

HAND SPECIMENS

The differences between the rocks, discernible in the two quarries, are even more obvious in the hand specimens.

In the *Pittsburg quarry,* the fresh rocks, dolostones and limestones, are prevalently medium to dark medium grey (N5-6)[1]. They are uniform in colour, rarely narrowly-striped or mottled. In beds containing both limestone and dolostone the differences in colours of the mottled rocks are very

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Photo 2–Lower lift of the Uhthoff quarry, in Member A of the Gull River Formation. Thick- to medium-bedded limestone underlying broken, buff dolostone. The face of this lift is 27 feet (8.3 m) high. Photo by J. Mantuani.

[1] Colour symbols from Munsell's Rock-Color chart (Rock-Color Chart Committee 1963).

distinct. The weathered limestones are medium to light grey (N5-7); the weathered dolostones are greenish grey (5G6/1 or 5GY6/1).

The smooth surface of limestones, typical of lithographic and sublithographic varieties, and the rough surface of dolostones help to distinguish these two rocks in the field. Strongly dolomitized limestones are however, similar to dolostones. The few samples containing many quartz grains have a surface similar to that of fine-grained sandstones.

Stylolites and argillaceous seams are scarce in the Pittsburg rocks. The argillaceous concentrations and partings are usually darker than the main rock. The darkest interbed visible at the bottom of the middle lift is a dark grey (N3), finely striped, compact rock, 20 mm thick, intercalated between shaly partings of the same colour.

Examinations of the mottled limestone samples from the *Uhthoff quarry* show that the mottles are formed by dolomitic concentrations in an aphanocrystalline limestone. The variety with the small, contorted, convoluted and oval mottles is pale brown (5YR5/2) with pale yellowish brown (10YR7/2) in coarser grained, dolomitic mottles. The colour differences are less pronounced in the fresh upper limestones with the irregular dolomitic patches and short bandings which become greyish orange (10YR-7/4) on weathering. The chert nodules are slightly to distinctly absorptive and uniformly very light grey (N8), or banded with alternating narrow lighter and darker grey rims.

The two varieties of dolostones observed in the Uhthoff quarry are distinguishable in most hand specimens. The upper, greenish-weathering set contains mottled and uniform dolostones; the mottled dolostones, light grey (N7) with numerous greenish grey (5G6/1) aphanitic streaks, lenses or irregular patches, are restricted to a few beds at the top of the Member A. Several beds of this dolostone unit are slightly to distinctly absorptive.

The second set of dolostones which weather to buff colours are greenish grey (5GY6/1) to medium light grey (N6) on fresh surfaces. The partings are brownish grey (5YR6/1) to bluish grey (5B6/1). Argillaceous seams, a few millimetres wide, are observed at a few partings.

A distinct feature of the Gull River Member A is the occurrence of several relatively porous and absorptive silty-to-sandy dolostone beds which may contain alkali-reactive rock varieties. These rocks are discussed in Appendix II. They form part of the upper greenish dolostone unit in the Uhthoff quarry which is presently removed, and part of the 12-foot (3.7 m) dolostone unit in the Pittsburg quarry (shown on Figure 1 between depths of 25 feet (7.6 m) and 37 feet (11.3 m).

LITHOSTRATIGRAPHIC SECTION

The lithologic differences between the two quarries are illustrated in the lithostratigraphic sections of the Pittsburg and Uhthoff quarries shown in Figure 1. Although limestones and dolostones occur in both quarries, in the Pittsburg quarry the two rocks types alternate to form 17 units. The total thickness of dolostone beds in this quarry (39 feet or 12 m) is slightly greater than that of limestone beds. This repeated alternation is not matched by the lithology of the Uhthoff quarry. Within Member A, 9 feet (2.7 m) of dolostone overlies 18 feet (5.5 m) of limestone beds, one of which contains chert nodules. The dolostone including one sandstone interbed amounts to one-third of Member A in the quarry face.

The greenish absorptive dolostones have different settings in the two quarries as shown in Figure 1. In the Pittsburg quarry they are part of a 12 foot (3.7 m) dolostone unit overlain by younger limestones and dolostones of Member A. In the Uhthoff quarry the greenish absorptive dolostones are part of a 9 foot (2.7 m) dolostone unit and are in contact at the top with limestones of Gull River Member B. Not all beds in these dolostone sections contain alkali-reactive varieties.

BASIC COMPOSITION

Figure 2 shows the great variation in composition of the rocks of Member A. This figure is a graphic representation of the basic compositions of all samples of the Gull River Member A from the Pittsburg and Uhthoff quarries for which the calcite to dolomite ratios and the acid-insoluble residues have been determined. On the graph are plotted 57 recent samples and 57 samples tested previously for alkali reactivity. Since few shaly interbeds were observed in the faces of both quarries, only two samples of apparent shaly interbeds were analyzed for basic composition. Several hand specimens contained narrow argillaceous partings or surface films, which caused slight increase in the percentages of acid insolubles. One sample of chert from the Uhthoff quarry was also analyzed.

The most characteristic feature of the samples taken from the two quarries is that limestones contain less noncarbonate impurities than dolostones. Similiar results have been obtained for other areas of carbonate rocks, e.g. for Iowa carbonate rock aggregates (Roy *et al.* 1955). Recently examined limestones contain up to 21 percent and dolostones up to 49 percent noncarbonates. Figure 2 has a concentration of points at the calcite apex showing that two-

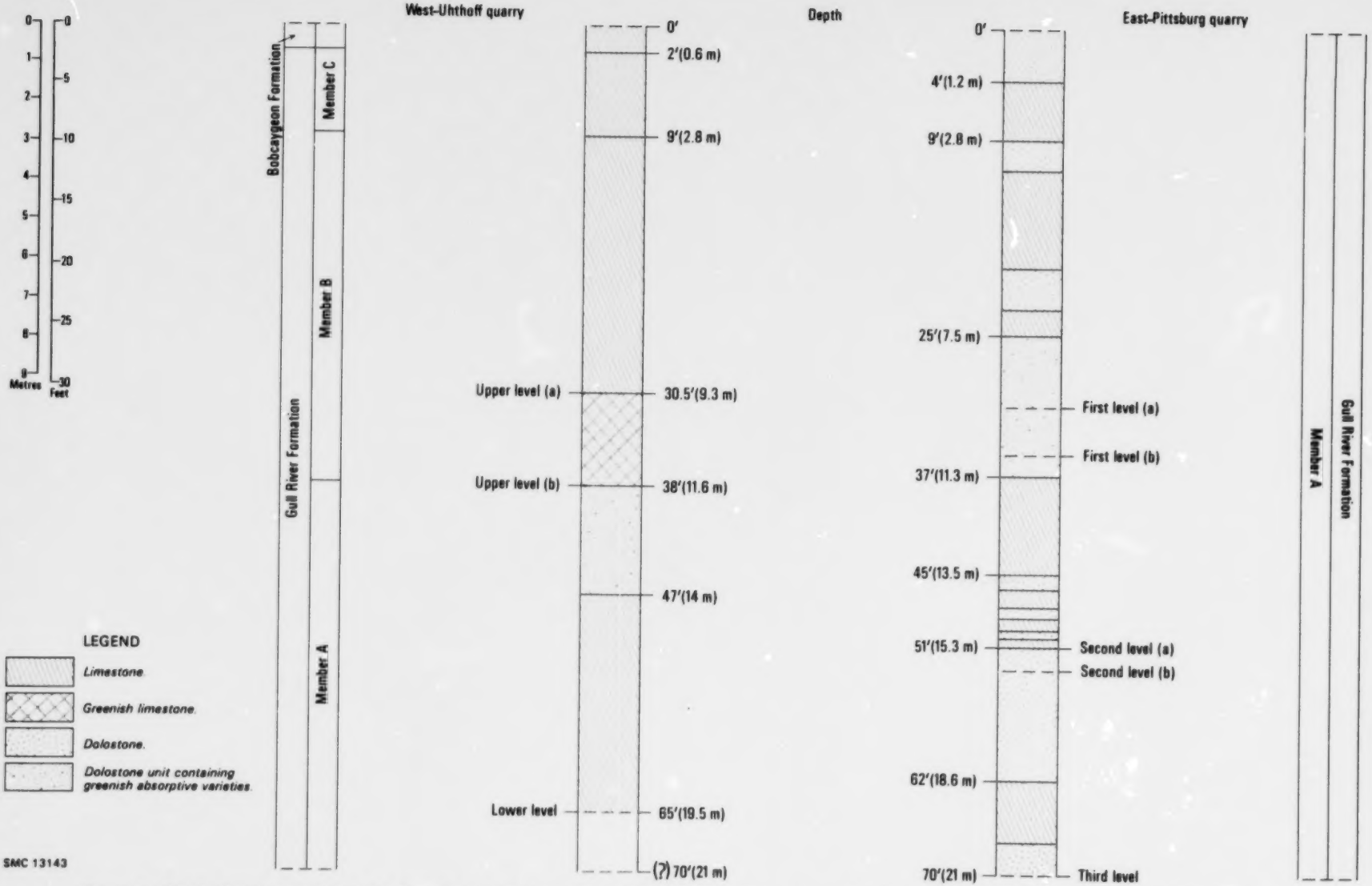

Figure 1–Lithostratigraphic section of the Gull River Formation in the Uhthoff quarry in the west and the Pittsburg quarry in the east. Note that the top 2 feet of the Uhthoff quarry are in the Bobcaygeon Formation; and that the levels are at different depths indicated by a and b in different parts of the quarries.

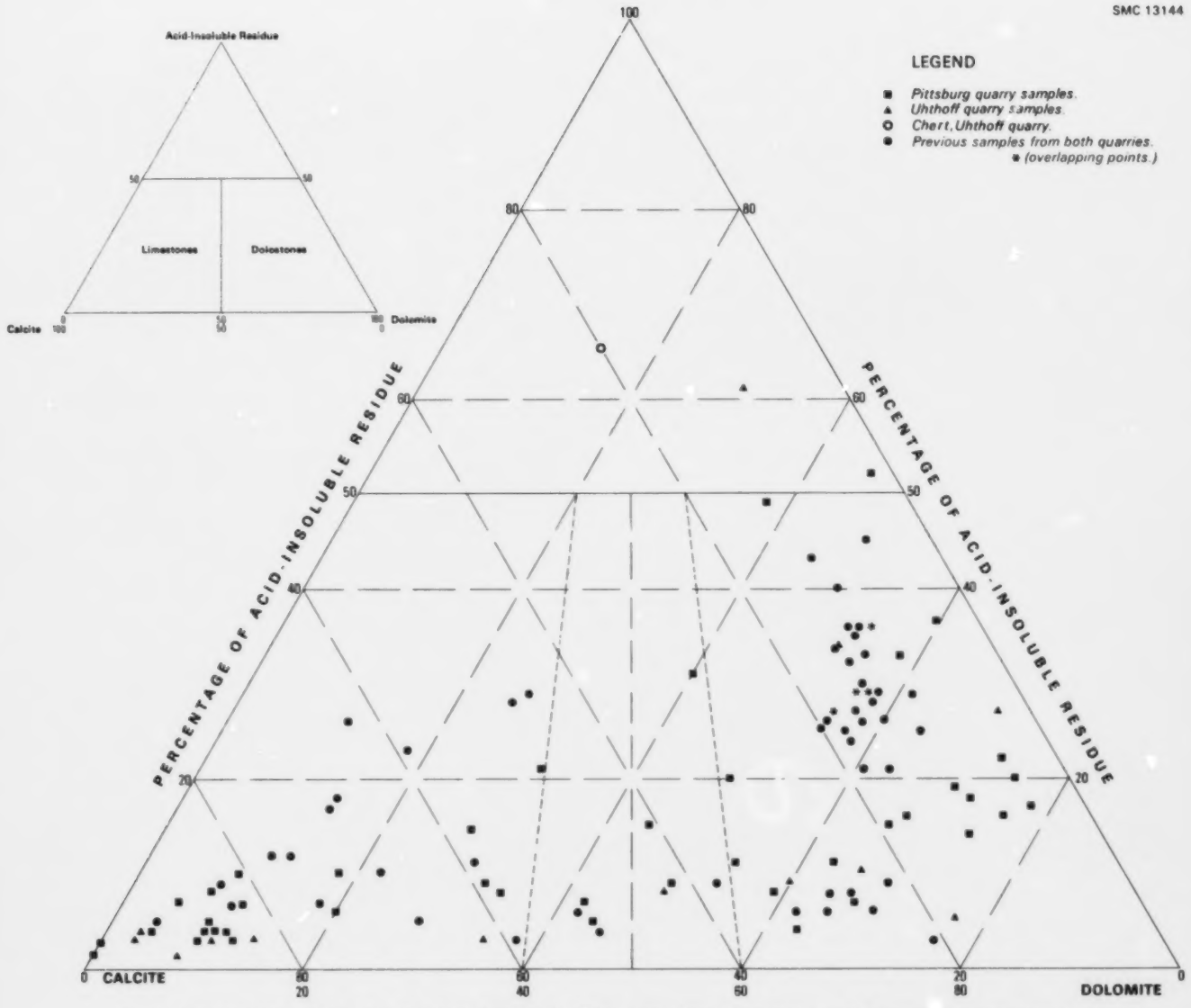

Figure 2–Basic composition of rocks from Member A of the Gull River Formation. Inset shows the compositional range of limestones and dolostones.

thirds of the limestones have more than 80 percent calcite. The dolostone points are scattered throughout the dolostone field demonstrating the very great variation in the composition of this group. Dolostones with more than 80 percent dolomite were not found in the Gull River Member A.

The points in the upper field of the triangle, the field of noncarbonate rocks, require some interpretation. Two of the three points represent samples containing dolomite as the main carbonate constituent; one is a dolomitic silty sandstone, while the other sample with 52 percent noncarbonates is a rock which has the megascopic appearance of a dolostone. On the other hand, the point in the dolostone field with 49 percent insoluble residue represents a sample with the appearance of a shaly interbed. This indicates that the thin-bedded interbeds are rocks that are borderline between dolostones and shale and that the appearance of the hand specimens may be misleading. The third point in the noncarbonate field represents the Uhthoff chert.

Alkali-reactive carbonate rocks are often considered to have calcite to dolomite ratios in the range of 0.67 to 1.5 corresponding to 40 to 60 percent calcite or dolomite in the carbonate portion of the rock (see Appendix II). Of the previous samples from both quarries tested for alkali reactivity, only three have ratios in the above range, although many samples expanded excessively in sodium hydroxide. Of the new samples which represent almost all beds in both quarries, only six have ratios in the above range.

Figure 2 also shows that 26 samples of the impure absorptive calcitic dolostone variety from both quarries are clustered in the upper right portion of the dolostone field. This demonstrates the great similarity in the basic composition of these particular rocks in both quarries.

MINERALOGY

The following constituents were observed in thin sections and were determined by R. Laakso using X-ray diffractometry: calcite, dolomite, clay minerals, quartz, feldspars, pyrite, and celestite. Calcite occurs as anhedral grains with a great range in size from aphanocrystalline in lithographic limestone to coarse-grained patches which are visible megascopically in a few dolostone beds. Dolomite occurs in euhedral or subhedral rhombohedrons with a smaller size range, from finely to medium crystalline.

The X-ray results of the insoluble residues show that quartz is present as a major constituent, and that potassium feldspar is more abundant than plagioclase. The clay minerals illite and chlorite are usually present in minor amounts. Several samples contain illite interstratified with minor amounts of an expansive clay mineral. This mineral is not limited either to one rock-type or to specific levels in the quarries.

Celestite (strontium sulphate) occurs in the form of single grains, grain accumulations and occasionally veinlets in dolostones at two levels in the Kingston area. All samples of Member A contained at least traces of sulphates; the maximum was 3.4 percent calculated as gypsum. No gypsum or anhydrite was observed in the thin sections. The amounts of sulphates are somewhat higher in the eastern area than in the western area, which agrees with the findings of Mukherji and Winder (1970). Pyrite in small crystals and limonite as a weathering product were detected in several samples and are responsible for the buff and greenish colours.

Among the numerous results of mineral investigations of the Kingston reactive rocks published by Gillott (1963, p. 765, 773) only a few specific results are mentioned in the following: calcite and dolomite have a nonideal lattice development, illite appears to be intergrown with organic material, and chlorite is also present in the samples examined by Gillott but swelling clay minerals are absent.

Mukherji and Winder (1970) report that although acid-insoluble residues constitute a small portion of the rock mass in the Gull River Formation, a wide range of mineral species is present indicating the closeness of Precambrian, silicate rock masses during deposition. Authigenic sulphide minerals, galena, pyrite and sphalerite occur in very low amounts in both quarries.

Petrography of Pittsburg Quarry

COMPOSITION

The quarry is represented by 43 new samples. Seventeen rock units can be distinguished on the basis of alternation of dolostones and limestones. There are even more units recognizable if one considers variations in the amounts of noncarbonate impurities, dolomite and calcite, and textural differences. The quarry contains a whole range of carbonate rocks from pure limestones to intensely dolomitized limestones and dolostones containing negligible amounts of calcite. "High calcite" limestones are found in several horizons and some slightly dolomitized beds are present in almost all limestone sets. Five feet of pure limestone occurs near the quarry floor. Dolostones with negligible calcite are present in some beds in the middle portion of the quarry.

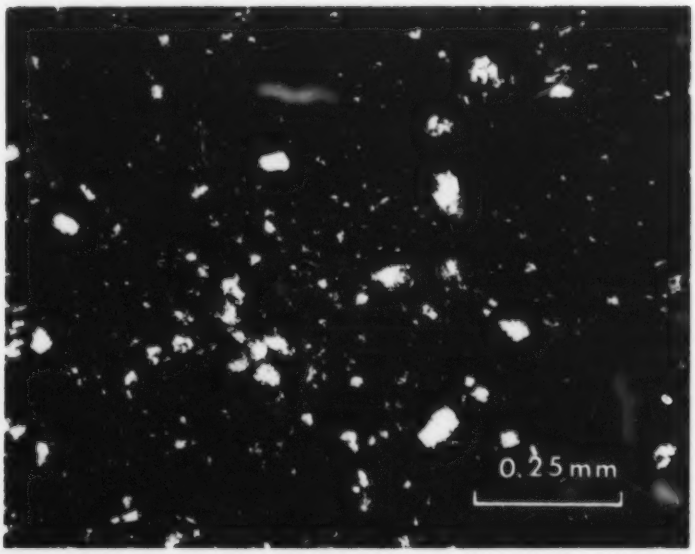

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Photo 3–Pittsburg quarry, Member A of the Gull River Formation; photomicrograph of slightly dolomitized micrite showing rhombohedrons of dolomite in a calcite matrix. Photo by W. Hicks.

Rocks with calcite to dolomite ratios between 0.67 and 1.5 were found in six samples. These rocks, which are dolostones or limestones (a distinction which loses its significance with the ratio close to unity), occur at different levels in the quarry. Ten other samples with relatively high dolomite or calcite contents illustrate gradational dolomitization.

IMPURTIES

Of the noncarbonate impurities, the most important and locally the most abundant are the clay minerals illite and lesser amounts of chlorite. Minor amounts of an expansive clay mineral interstratified with illite occur in both limestones and dolostones. Small lens-like, irregular or interstitial, greenish micropatches of clay minerals are observed in dolostones rich in insoluble residues. Clayey concentrations such as stylolites, argillaceous seams, and interbeds of calcareous shale are rare. The calcareous shales consist of interlaminations of clay and carbonate laminae.

Quartz grains occur sparingly in the limestones but are more abundant in dolostones below the 20-foot (6.1 m) level. In the limestones, the terrigenous quartz grains are silt-sized and angular to subangular. On the other hand, in the quartz-rich dolostones the quartz grains may be subrounded and vary in size from silt to fine-sand with a few rounded grains of coarse-sand size. In such rocks quartz occurs in a net-like distribution enclosing areas of microcrystalline dolomite, clay minerals and probably calcite. Quartz-rich interlaminations are rare and seem to be concentrated in calcareous shales. Recrystallized quartz prisms occur in several limestone beds and also in those few dolostone areas that have celestite concentrations.

Feldspar grains are rare and occur as orthoclase, microcline, and occasionally as twinned plagioclase.

TEXTURE

Most thin section observations reveal that the dolomite was introduced after the formation of the limestone; by observing rocks from various beds in the quarry, all the steps of dolomitization are seen. The original limestones seem to have been calcitic mudstones, micrite or perhaps microsparite with anhedral calcite grains. The resulting uniform limestones are usually slightly dolomitized and contain disseminated, finely to very finely crystalline dolomite rhombohedrons (Photo 3). Several limestone varieties contain traces of burrowings of organisms and (or) various amounts of pellets and intraclasts in a micritic or microsparry matrix; or they contain sparry calcite cement in small dismicritic areas. An interlaminated texture with burrows occurring in the form of repeated parallel laminae are visible in a few varieties.

The extent of dolomitization of different rock-types varies greatly. In the dismicrites, the dolomite rhombohedrons are frequently almost evenly distributed while in the dolomitic limestones grading to dolostones, the dolomitization was frequently

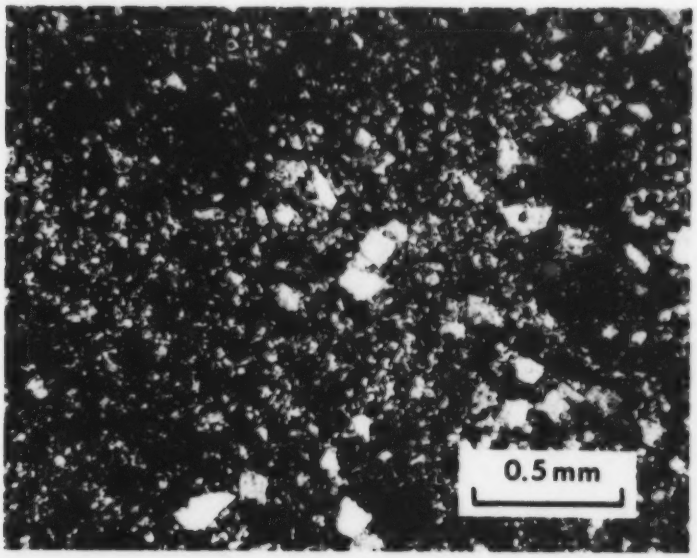

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Photo 4–Pittsburg quarry, Member A of the Gull River Formation: photomicrograph of silty to sandy, argillaceous, calcite-bearing dolostone. Photo by W. Hicks.

selective, affecting the matrix or sparry cement but not the pellets and intraclasts. The calcitic dolostones grading in composition to dolomitic limestone contain only remnants of micritic pellets and intraclasts. The size of the dolomite grains varies from very finely crystalline to medium crystalline, and many samples appear to contain two generations of dolomite. The larger sized grains with dusty (clayey) inclusions are restricted to a few beds.

Dolostones rich in insoluble residues with prominent silty to fine-sandy quartz and clayey patches have a texture similar to that of clastic rocks (Photo 4). The amount of calcite is relatively low in this group.

The scarcity or absence of fossils is a typical feature of the Member A rocks.

Fresh limestones are dense with absorptions of 1 percent or less, whereas the dolostones have absorptions up to 5.3 percent by weight (Dolar-Mantuani 1971a). The limestones are normally less weathered than the dolostones.

CLASSIFICATION OF PITTSBURG QUARRY ROCKS

The interbedding of a whole range of carbonate rocks from pure limestones to silty argillaceous dolostones makes a simple classification impossible. The following rock-types were identified in the quarry:

Pure to almost-pure limestone;
Slightly argillaceous to distinctly argillaceous limestone;
Slightly to intensely dolomitized limestone which may be argillaceous to various degrees;
Slightly to distinctly calcitic dolostone, usually argillaceous;
Silty- to sandy-argillaceous dolostone;
One sample of a silty dolomitic shale.

According to their texture, the rocks are micrite and dismicrite both dolomitized to various degrees, with pellet-bearing dismicrite, pelsparite and intrapelsparite in some laminae. The rocks may be stylolitic or argillaceous. The dolostones are finely to medium crystalline and may contain micritic or pelmicrosparitic intraclasts.

Petrography of Uhthoff Quarry

Sixteen new thin sections were made of the Member A rocks from the Uhthoff quarry. The Uhthoff rocks are more homogeneous than those from the Pittsburg quarry. Because limestones and dolostones occur in the Uhthoff quarry in two separate sections, the mircroscopic characteristics of each rock group are discussed separately.

LIMESTONE

Limestones are more abundant than dolostones in the Uhthoff quarry. They are all low in acid-

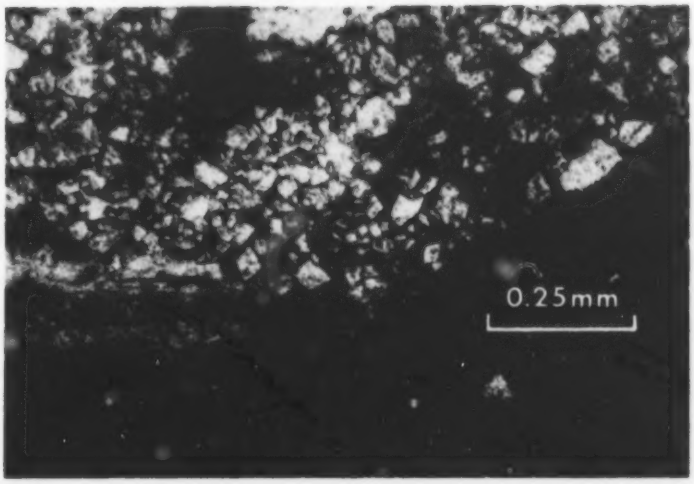

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Photo 5–Uhthoff quarry, Member A of the Gull River Formation; photomicrograph of micrite with dolomitized nodule (top of photo), fossil remnants (below nodule on left side), and micritic intraclasts (below nodule on right side). Photo by W. Hicks.

insoluble residues and usually have a low dolomite content. The exact ratio of limestone to dolomitic nodules in the coarse mottled rocks is impossible to determine in thin sections, because of the large size of the nodules. Although the samples used for determination of calcite to dolomite ratio by the X-ray diffraction method contained some dolomitic nodules, none were found to have a ratio between 0.67 and 1.5; only one sample from the entire quarry, a dolostone, had calcite and dolomite in about equal amounts (see Figure 2).

In the mottled rocks the dolomitic nodules consist of finely crystalline dolomite in a microsparry matrix of calcite (Photo 5). The ratio of calcite to dolomite in the nodules is variable, but it is most frequently 2 to 1. The dolomitic nodules become scarcer in the upper beds of the quarry. In a whitish weathered, slightly mottled limestone bed immediately below the buff dolostones, no dolomitic crystals were visible in the thin section.

In the upper mottled unit the limestone between the dolomitic nodules is micritic and also stylolitic in some beds. There are no pellets in this variety but intraclasts are locally well defined in the calcitic areas. The limestones of the lower finely mottled unit are micritic or microsparry containing some pellets, typical algal intraclasts, and fossils, the last usually in a microsparry matrix.

Sporadic clastic quartz grains of very-fine-sand size are found only in the bed above the cherty limestone bed. The chert nodules are aphanocrystalline, almost isotropic and contain rhombohedrons of dolomite. This cherty limestone bed seems to be richer in dolomite than the other beds. The interbed of calcirudite forming the quarry floor contains oval algal interclasts averaging 5 mm in length, with pyrite and oolites. Sparry recrystallized cement is developed between the intraclasts. This interbed is the only rock in which oolites were found. The microsparry limestone below the quarry floor, at the 66-foot (20.1 m) level contains numerous minute pyrite cubes concentrated in inconspicuous stripes.

DOLOSTONE

There is a clear difference in composition between the two types of dolostones occurring in Member A of this quarry. The buff-weathered dolostones are slightly impure, calcite-bearing rocks which contain gradationally more calcite toward the upper part of the section. The greenish weathered dolostones are highly impure rocks with a low calcite content. This dolostone unit includes a dolomitic sandstone bed which has the appearance of a uniform dolostone.

In thin sections, the buff dolostones are a uniform mixture of very finely crystalline dolomite rhombohedrons and micritic calcite. The beds richer in calcite contain a few macrofossils and small relict patches of micrite in a very finely crystalline to aphanocrystalline dolostone (Photo 6). A few former voids and narrow veinlets are filled with sparry calcite.

The greenish weathered dolostones are heterogeneous, and two main rock types can be distinguished: one is a homogeneous, silty or rarely sandy, argillaceous dolostone containing quartz and feldspar grains, and a few small patches of clay minerals in a finely crystalline mass of subhedral dolomite. Calcite occurs in a few poikilotopic grains. The second type

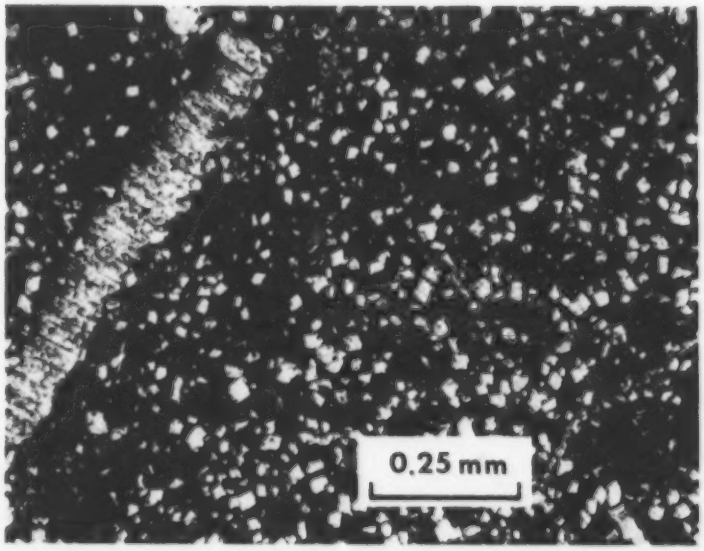

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Photo 6–Uhthoff quarry, Member A of the Gull River Formation; photomicrograph of dolostone rich in micritic remnants. The macrofossil is about 1 mm long. Photo by W. Hicks.

is most commonly a mottled, argillaceous, silty to sandy dolostone with quartz as the main impurity. The greenish mottles are aggregations of microcrystalline dolomite, clay minerals, micritic intraclasts, and sand-sized concentrations of clay. In some varieties the clay minerals predominate over quartz. These greenish weathered dolostones are usually absorptive and in thin sections are similar to absorptive dolostones in the Pittsburg quarry (see Photo 4).

The homogeneous, fine- to medium-grained, compact dolomitic sandstone contains poorly sorted quartz grains and some feldspar grains in a finely crystalline cement of dolomite and calcite with minor amounts of illite. Dolomite and subordinate calcite also occur in lenses and laminae.

CLASSIFICATION OF UHTHOFF QUARRY ROCKS

The limestones are almost-pure micrites, usually dolomitized in nodules to various degrees. In these nodules the concentration of dolomite decreases outward into the micrite.

The dolostones are slightly-impure, calcitic dolostones, and silty- to sandy-argillaceous, or argillaceous silty, calcite-bearing dolostones. One sample was a calcite-bearing dolomitic argillaceous sandstones, and one was a dolomitic aphanocrystalline chert.

GULL RIVER MEMBERS B AND C

Uhthoff Quarry

The upper lift of the Uhthoff quarry is developed in Members B and C of the Gull River Formation. This upper lift consists of 29 feet (8.8 m) of Member B and 7 feet (2.1 m) of Member C. The uppermost 2 feet (0.6 m) at the top of the quarry are Bobcaygeon rocks (see Figure 1 and Photo 7).

Alternate units of thin beds, and medium to thick beds are visible in the quarry face (Photo 7). The thinner beds do not contain enough argillaceous material to be classified as typical interbeds. Two pairs of beds that are a whitish colour on the slightly weathered surfaces are prominent among the medium to thick beds; they can be traced for a great distance, and make excellent marker horizons for the Gull River Member B. The upper marker bed forms the top of Member B. A similarly prominent, whitish-weathering limestone occurs at the top of Member C in conformable contact in one bed with the Bobcaygeon limestone above.

The 7½-foot (2.3 m) limestone unit at the bottom of Member B can be distinguished from the other Member B limestones by its distinct greenish hue which deepens on weathering. The rocks above are weathered buff. This unit forms the floor of the

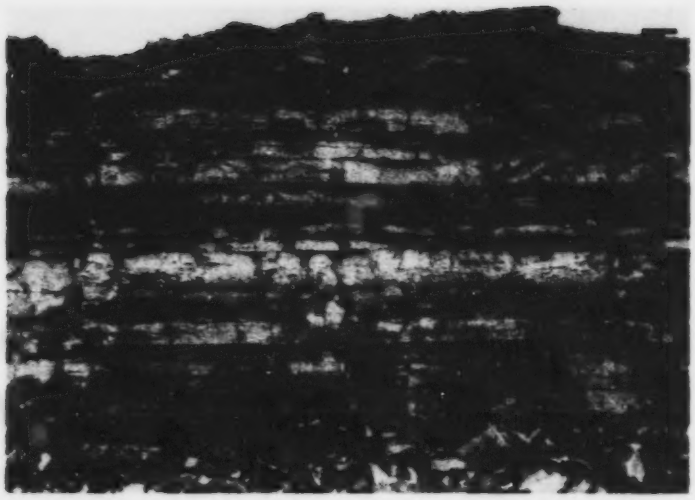

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Photo 7–Upper lift of the Uhthoff quarry showing Member B of the Gull River Formation (B on photo), Member C of the Gull River Formation (C on photo), and the Bobcaygeon Formation (D on photo). A 7½ foot (2.3 m) thick unit of greenish, dolomitic limestone is indicated by a, and whitish, thick- to medium-bedded markers by b and c. The quarry face is about 38 feet (11.6 m) high. Photo by J. Mantuani.

upper lift in the northwestern portion of the quarry, and is not used as concrete aggregate.

According to Liberty and Bolton (1971, p.12), Member B and C of the Gull River Formation comprise the high-calcium limestone section in which oolitic and clastic pellets of lithographic limestone are evident. Fossils are relatively rare and are mainly ostracodes. Hewitt (1960, p.31) described the rocks comprising Member B and C as:

> . . . grey-weathering, dense, medium-bedded lithographic limestone. . . . Within the . . . lithographic beds there are two prominent white- or silver-grey-weathering massive limestone marker beds. . . . There is some mottling and colour lamination in the cryptocrystalline limestone.

SAMPLES

Twenty samples were collected from Member B and three samples from each of Member C and the Bobcaygeon Formation. Thin sections were prepared from all Member C and Bobcaygeon samples and from 16 Member B samples. In addition, 17 samples collected in 1962 from the upper lift of the quarry face were examined in thin section.

HAND SPECIMENS

The rocks in Members B and C are aphanic limestones, more or less homogeneous and dense, with a tendency to fracture conchoidally. The most typical feature of Member B beds is the presence of narrow, wavy, bifurcating and intersecting stylolites which increase in number toward the tops of the beds that are covered by shaly partings. The multiple stylolites may enclose limestone lenses in the shaly partings. A sample of the narrow stylolitic interbed between the Member A dolostones and the Member B dolomitic limestones has a lens-like texture visible on the cross section.

The limestones are light gray with a buff tint and are usually striped in hues of grey. Stylolites and partings are mostly brownish grey in the upper portion of Member B but greenish hues prevail in the lower portion of this Member. Colour differences become more evident on weathering, especially in the greenish section and in the whitish marker beds; the remaining beds weather buff.

The samples of the Member C beds are very uniformly light grey and contain few stylolites except for one sample of a distinctly thicker, buff and grey, mottled bed.

BASIC COMPOSITION

The lithostratigraphic section of the Uhthoff quarry (see Figure 1) shows that the Gull River Members B and C consist of limestones only. The basic composition is illustrated by 20 recent samples and 10 samples collected in 1962 for alkali reactivity studies. On the two-component semilogarithmic graph (Figure 3), the percentages of dolomite are on the abscissa and the acid-insoluble residues are on the ordinate (see "Methods of Examination").

The graph shows that the recent samples taken from the buff-weathered beds of both Members are pure or almost-pure limestones containing up to 5 percent dolomite. Four samples contain more than 10 percent insoluble residues. The highest insoluble-residue values were 13 percent in a narrow stylo-

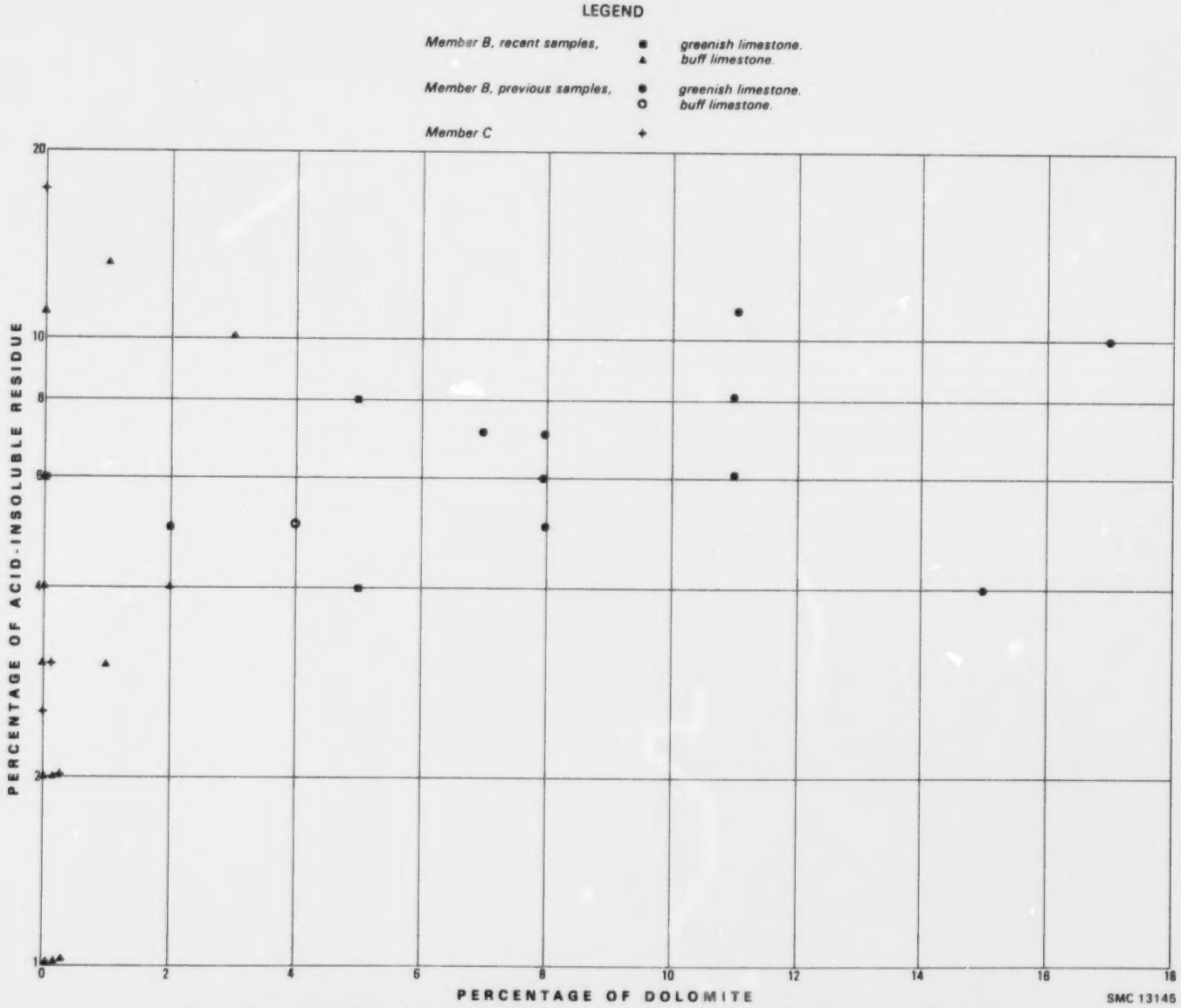

Figure 3–Basic composition of rocks from Members B and C of the Gull River Formation, Uhthoff quarry.

litic interbed between the bottom of the greenish beds and the top of Member A, and 17 percent in a mottled limestone with a distinct shaly parting from Member C.

The sample of the argillaceous parting occurring at the contact between the Member B limestones and the Member A dolostones is included in the Member B section because of its compositional and textural similarity to the Member B rocks discussed above.

The previously analyzed samples were all taken from the greenish beds in the 7½-foot (2.3 m) bottom section of Member B, except for one sample from just below the upper whitish marker beds of Member B (see Photo 7). This sample conforms in composition with the recent samples, but the other previous samples contain from 7 to 17 percent dolomite. Thus, the old samples suggest that the greenish unit is a more highly dolomitized limestone than the recent samples from the same unit. They are generally somewhat higher in impurities than remaining beds of Member B and C (see Figure 3). The greenish beds however, cannot be considered as transitional rocks between the underlying silty impure dolostones of Member A and the almost-pure limestones of Member B because the greenish beds are significantly different in texture from the dolostones but are very similar in texture to the limestones.

MINERALOGY

The mineral compositions of the Gull River Members B and C are very uniform. Calcite in anhedral grains is the major constituent and apparently the only carbonate mineral in many samples. Scarce dolomite was observed in samples from the lower half of Member B.

Silty quartz is the major clastic constituent of the acid-insoluble residues, potassium feldspar occurs in moderate amounts and plagioclase is a minor constituent. In a few samples the silty quartz is much scarcer and plagioclase is absent. The clay minerals chlorite and the more abundant illite usually occur in moderate to minor amounts. An expanding clay mineral interstratified with illite was found in samples from the 8½- to the 13-foot (2.6 m to 4.0 m) section, i.e. below the lower whitish marker and above the 7½-foot (2.3 m) greenish unit. Although the amounts of this mineral were more than minor in the residue, it should be noted that this unit contains only 4 to 10 percent insoluble residue which includes quartz, feldspar and clay minerals. The amount of expanding clay minerals must be therefore very low in the rock. The greenish coloured stylolites in limestones from the greenish beds have an X-ray pattern indicating mica (Laakso, personal communication). Their medium greenish grey colour (5G5/1) suggests the presence of glauconite. Hewitt and Vos (1972, p.39) mention the occurrence of glauconite in a nearby quarry. Pyrite occurs in a few samples in amounts detectable by X-ray.

PETROGRAPHY OF MEMBER B

The rocks are very finely crystalline to aphanocrystalline limestones. They are dismicrites and contain intraclasts and (or) pellets in streaks, laminae or large areas to cover a whole thin section. The uniform portions between the burrows and the disturbed texture are slightly coarser grained and may contain faintly recognizable algal intraclasts. Interlamination of varieties with small differences in texture are repeatedly found in several samples on a less than millimetre scale. Stylolites are rare and small dolomite rhombohedrons are perceptible in only a few samples from Gull River Member B. Fossil remnants and quartz grains are rare and apparently absent in several samples. The limestones in Member B (Photo 8) are very similar to the dismicrites in Member A.

In fresh hand specimens and in thin sections, it is very difficult to distinguish the whitish markers from rocks in other beds below and above. The greenish tint of rocks from the bottom section of Member B is produced by greenish stylolites apparently containing glauconite; the intensity of the tint depends mainly on the number of stylolites whose colour deepens on weathering. There is no significant difference in the thin section appearance of the limestones of this unit and the buff-weathered limestones above; but the old samples from the greenish beds have higher dolomite contents as shown in Figure 3.

PETROGRAPHY OF MEMBER C

Two thin sections made from samples of this member are homogeneous, stylolitic, fossil-bearing, almost-pure limestones of the pelsparite or pelmicrosparite type (Photo 9). The mottled bed in this Member is very similar to the mottled bed immediately below the dolostone unit in Member A. The significant difference is that the mottled bed of Member A is practically a pure limestone, whereas the Member C rock is an argillaceous stylolitic limestone; it is richer in fossils than the other beds in Member C.

CLASSIFICATION

In general the rocks of Member B and C are pure to slightly impure, stylolitic limestones, rarely

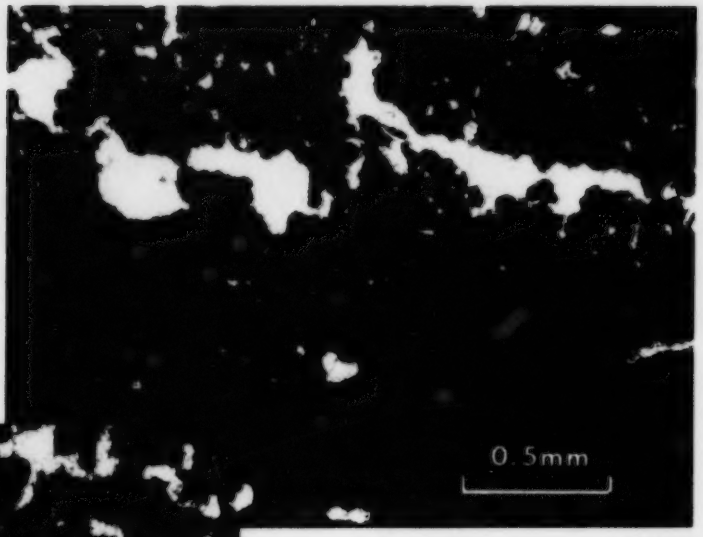

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Photo 8–Uhthoff quarry, Member B of the Gull River Formation; photomicrograph of dismicrite with patch of algal pelsparite (upper half of photo); light-coloured sparry calcite fills voids. Photo by W. Hicks.

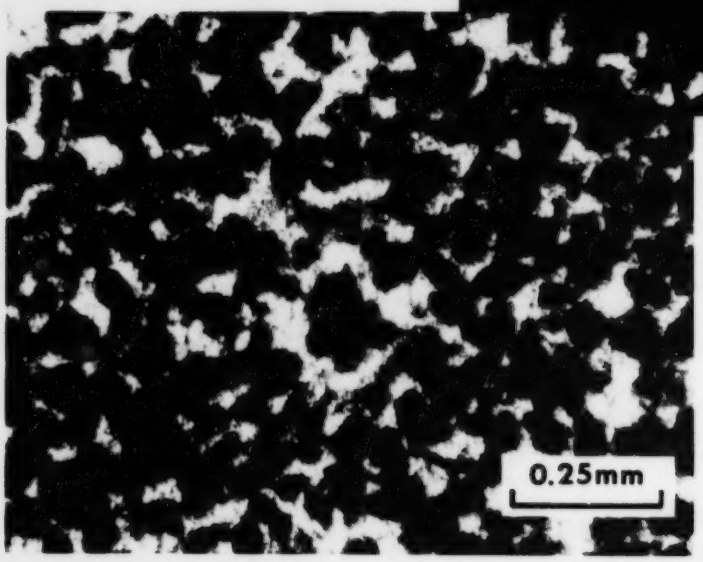

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Photo 9–Uhthoff quarry, Member C of the Gull River Formation; photomicrograph of pelsparite with very finely crystalline microsparite remnants. Photo by W. Hicks.

argillaceous. The Member B rocks are dismicrites, rarely pellet- or intraclast-bearing; a few samples are intrapelsparite or pelsparite in areas of several square centimetres. Dolomite is seldom present in more than trace amounts and fossils are scarce. The Member C rocks are pelsparites or pelmicrosparites and are locally fossil-bearing.

In general, the Gull River rocks contain few fossils recognizable in hand specimens. An algal origin of the micritic and microsparry rocks is indicated by the slight heterogeneity of the grain size of calcite and locally by the presence of extremely fine needle-like forms. These features distinguish the Gull River rocks from the Bobcaygeon rocks which are usually intraclast-bearing biopelsparites or fossil-bearing intrapelsparites. The pelsparites and pelmicrosparites of Gull River Member C are usually more homogeneous in grain size and contain fewer fossils than the Bobcaygeon rocks.

PROPERTIES OF GULL RIVER ROCKS RELEVANT TO INDUSTRY

The quarried Gull River rocks are fresh and compact. They usually have a low clay content, good shape factor (cubic) on crushed material, low absorption and low losses when subjected to the sulphate soundness test (ASTM Designation: C 88). These features apply generally to the limestones but not to all the varieties of dolostones. Several dolostones and a few limestone varieties are rich in argil-

laceous impurities. Concentrations of clay minerals in stylolites, seams, or interbeds may produce weakness planes and may not be frost resistant, but the concentrations are usually scarce, and portions of them are normally lost during processing operations.

The clay minerals are illite and chlorite. Small micropatches of these minerals occur in some rocks, such as dolostones high in acid-insoluble residues. Some beds contain illite interstratified with an expansive clay mineral, but the amounts of the latter are very small. Usually it is absent or perhaps present in such small amounts that it is not detectable by X-ray even when concentrated in the acid-insoluble residues.

Chert may be present in some Gull River quarries, but if the entire quarry face is considered, the amounts are usually negligible. The chert from Paleozoic rocks is normally not alkali reactive but it is sensitive to frost (Dolar-Mantuani 1972, p.233).

In the two quarries examined, the limestones are less weathered than the dolostones. Some silty and sandy, weathered dolostones have absorptions greater than 5 percent and develop considerable cracking while stored in stockpiles. The weathering seldom lowers the quality of the rock to such a degree that the material is unsuitable for any practical use. Only one dolostone bed in the Pittsburg quarry was found to be friable and crumbling, probably because of an abundance of original sulphides.

When limestones and dolostones are interbedded in sections bed by bed, or in sections of several beds, the crushed material produced will not be uniform, and changes in the quality of the product from different lifts may be expected. Dolostone is frequently of poorer quality than the limestone.

The extremely fine grain sizes of the aphanocrystalline limestones, that is, the micrites and dismicrites, and the compactness of these varieties may cause some problems because of poor adhesion of asphalt or cement to the smooth particle surfaces.

The most serious problem, however, is the alkali reactivity of some Gull River beds. Fortunately, only two submembers of the Gull River Formation contain alkali-reactive rocks. Most quarries in the Gull River Formation are not worked in these submembers and where they are, corrective measures can be taken to prevent the detrimental effects of the reactive rocks when they are used as concrete aggregates (see Appendix II).

Other uses of the rock are not affected by the expansive property of such varieties. According to Newlon, Sherwood and Ozol (1972) "aggregate classified as reactive in portland cement concrete is normally acceptable for other uses, such as base material, bituminous concrete, etc." Material from several quarries suspected of containing, or proven to contain reactive rocks is used for these purposes only. The description of rock use in the report by Hewitt and Voss (1972) shows that this is the practice. Selective quarrying can be and is used successfully to eliminate harmful beds such as argillaceous beds, the stylolitic limestone interbed at the top of the Member A dolostones and the silty to sandy, argillaceous dolostones which are of poor quality because of high absorption.

Slightly reactive rocks can be used as aggregate in concrete for dry buildings, especially when the reactive rock is diluted with material from other beds which do not contain alkali-reactive varieties. In a few instances low alkali cement is needed.

A geologist or petrographer familiar with the problem or reactivity can establish whether a quarry is located in the reactive submembers. If it is, the material must be examined for reactivity (Appendix II).

The nonreactive Gull River rocks may be used for road material, concrete, railway ballast, riprap and for shore protection provided that there are no distinct argillaceous partings present. Crushed limestone very low in insoluble residue, from the Black River Formation corresponding to the Gull River Formation, was successfully used for manufacturing fine aggregate for concrete in the Robert Saunders Generating Station at Cornwall. Years ago, Gull River rocks were widely used as building stone.

Bobcaygeon Formation

The Bobcaygeon Formation is a lithogenetic unit lying between the lithographic limestone of the Gull River Formation and the equally distinctive interbedded limestone and shale of the Verulam Formation (see Table 2). For the most part, it is medium- to thin-bedded, grey calcarenitic and sublithographic limestone (Liberty 1971, p.5).

Kirkfield Quarry

One of the largest quarries excavated mainly in the upper Bobcaygeon is located near Kirkfield Village in Victoria County. According to the lithostratigraphic units proposed by Liberty (1963, p.8), the lower 36 feet (11.0 m) of the quarry face is Bobcaygeon, and the upper 5 feet (1.5 m) is in the Verulam Formation. The Bobcaygeon beds correspond to the biostratigraphic Lower Trenton/Kirkfieldian Substage with *Dalmanella* and crinoid beds, and the Verulam beds correspond to Middle Trenton *Prasopora* beds defined by Hewitt (1960, p.40-41).

The quarry was operating on previous visits by the author in 1952 and 1962 but on a recent visit the quarry was flooded to within 15 feet (4.6 m) of the top. The description of the quarry was taken mainly from notes made during the 1952 visit but a few samples collected recently from the uppermost beds were included in the petrographic examinations. Because of the shortcomings in sampling the abandoned Kirkfield quarry, additional data from the Marysville quarry, operated in the Bobcaygeon Formation, are used for characterization of this Formation.

The quarry is a pit type, almost circular, with a diameter of about 350 yards (320 m). The quarry face consisted of continuous, more or less horizontal beds, weakly undulating in a few areas. The thickness of the beds varied considerably (Photo 10), the average thickness being 4 to 5 inches (10 to 12.5 cm). The maximum bed thickness of about 23 inches (58 cm) was observed in the lower portion of the quarry where the Bobcaygeon beds are more massively developed. About three-quarters of the quarried rock came from the thicker beds of fossiliferous limestone. About 20 percent of the quarried material came from the thinner beds of homogeneous aphanic limestone and from more uniform and finer grained portions of several fossiliferous limestone beds. Stylolitic accumulations, shaly partings less than 5 mm in thickness, and argillaceous seams and narrow interbeds amounted to about 5 percent of the quarried rock. All limestones were compact with only a few voids parallel to the layering in some beds.

Fissures and joints are relatively scarce and, when present, are more or less vertical. Several openings are covered with white calcite and minute pyrite crystals or, in weathered beds near the surface, with a thin brownish crust rich in limonite. The fissures have been widened by leaching. The distinctly weathered zone extends 6 to 7 feet (1.8 to 2.1 m) below the stripped surface.

The uppermost thin-bedded layers, weathering brownish along bedding planes and fissures, belong to the Verulam Formation. The usual darker colour of the Verulam limestone due to a slight increase in argillaceous content (Liberty and Bolton 1971, p.15) in comparison with the Bobcaygeon limestone, is not noticeable in this quarry because of the distinct weathering. A description of the weathered Verulam beds is included in the section on the Verulam Formation.

ODM9025

Photo 10–Kirkfield quarry (1952); medium- to thin-bedded Bobcaygeon limestone. Photo by M. Loughborough.

SAMPLES

Only two samples collected recently along the access road above the water level in the Kirkfield quarry are from the Bobcaygeon Formation. The following samples, collected in 1952 and 1962, were examined to get more information: eleven recently analysed pieces from blasted-rock piles, believed to be Bobcaygeon on the basis of thin section examinations and the position of the blasted pile; and six randomly selected concrete aggregate particles, 1½ inches to ¾ inch (37.5 mm to 19 mm) in size, the basic composition of which was previously determined. To further characterize the Formation, the percentages of previously determined acid-insoluble residues for 60 samples are included; these consisted of 44 randomly selected particles 1½ inches to ¾ inch in size, and of 16 representative ledge rock pieces.

The weathered Bobcaygeon rocks are represented by three samples from the uppermost beds in the Uhthoff quarry.

HAND SPECIMENS

The rocks are compact, homogeneous and aphanic, or fine- to medium-grained in beds rich in fossil fragments. The fossiliferous rocks have a geopetal fabric in several beds, with smaller and fewer fossils and (or) with shorter and more numerous argillaceous films in the upper portion of the same bed. Most of the ledge rock pieces, 15 to 80 mm in thickness, contain shaly partings on one or both sides parallel to the layering indicating frequent repetitions of argillaceous accumulations. The fresh rocks are medium grey (N5) to medium light grey (N6). Argillaceous films and partings are usually medium dark grey (N4). Weathering produces discolouration in brown hues, light olive grey (5Y5/1) to pale brown (5YR5/1). Slightly weathered rock may contain only a few brownish specks.

The more intensely weathered Bobcaygeon limestone from the Uhthoff quarry is typically fossiliferous and compact but strongly discoloured to a pale yellowish brown (10YR7/2). Shaly films and partings are absent.

BASIC COMPOSITION

The basic composition of the Bobcaygeon Formation is presented in Figure 4. Percentages of acid-insoluble residues are on the ordinate and percentages of dolomite on the abscissa (see "Methods of Examination").

The graph shows that the dolomite content is low and that 10 samples do not contain sufficient dolomite to give an X-ray diffraction pattern. The variation in the percentages of noncarbonate constituents is considerable. The average acid-insoluble residue, including the three Uhthoff samples is 7.9 percent with a range from 1.1 to 18.5 percent. Several samples of the homogeneous, finely to very finely crystalline varieties richer than average in quartz and argillaceous material are included.

The range of insoluble residues is further illustrated in Figure 5A which is a frequency distribution polygon of the acid-insoluble contents of the group of 60 samples from the Kirkfield quarry. The peak at 7 percent acid-insoluble residue shows that slightly impure limestones were abundant in the quarry, and that almost-pure limestones were rather frequent, but that some limestones rich in argillaceous material were also present. The average acid-insoluble residue of this group of samples is 10.8 percent. Thirteen percent of the samples had more than 20 percent noncarbonates. Only one sample of shale with about 80 percent acid-insoluble residue was found in the set. The presence of limestones with relatively high contents of argillaceous material and silica causes asymmetry in the curve (skewness) typical for most limestones in any formation (Folk 1964, p.53).

MINERALOGY

Calcite is the main constituent and dolomite is a very minor constituent in the rocks. The most abundant noncarbonate constituents are the clay minerals illite and chlorite. An expanding mixed-layer clay mineral was tentatively identified in five samples, in minor amounts in the insoluble residue. Clastic quartz and chert are less abundant than clay minerals, and potassium feldspar is still more subordinate. Pyrite and its weathering product limonite are accessory minerals together with gypsum which is a minor constituent in the acid-insoluble residues of all but two recent samples according to the X-ray analysis. Sulphates in trace amounts were detected only occasionally in the filtrates from the acid-insoluble residues of 60 samples. Biotite, muscovite and hornblende were found in single grains.

In the fossiliferous varieties, some macrofossil fragments contain chert inclusions. They consist of aphanocrystalline to finely crystalline quartz and fibrous chalcedony with a refractive index below 1.54. Chert with typical desiccation cracks was noticed in two fossils only.

PETROGRAPHY

The most abundant limestone varieties in the Kirkfield quarry are biopelmicrosparite and biosparite. Pelmicrosparites and biopelsparites are much less abundant.

The fossils are usually of the calcarenite size and macrofossils, 1 mm or more in size, are sporadic. The maximum size of fossil fragments observed was 15 mm. Several shells contain cherty inclusions, or chert forms a narrow rim on the slightly silicified shell. Up to one-half of a shell fragment is replaced by chalcedonic chert. Single cherty fossils are visible in many thin sections, and biosparite varieties with recrystallized fossils contain up to 5 percent cherty accumulations.

Pellets are frequent but rarely distinct. In stylolitic limestone varieties with repeated concentrations of clayey material in stylolites, pellets may be present in scarce intraclasts only. Up to 17 percent of the rock volume may be clayey material with scarce quartz finely disseminated in the limestone. Dolomite rhombohedrons were noticed in only one thin section containing about 5 percent dolomite.

Interlaminated texture is rare except for repeti-

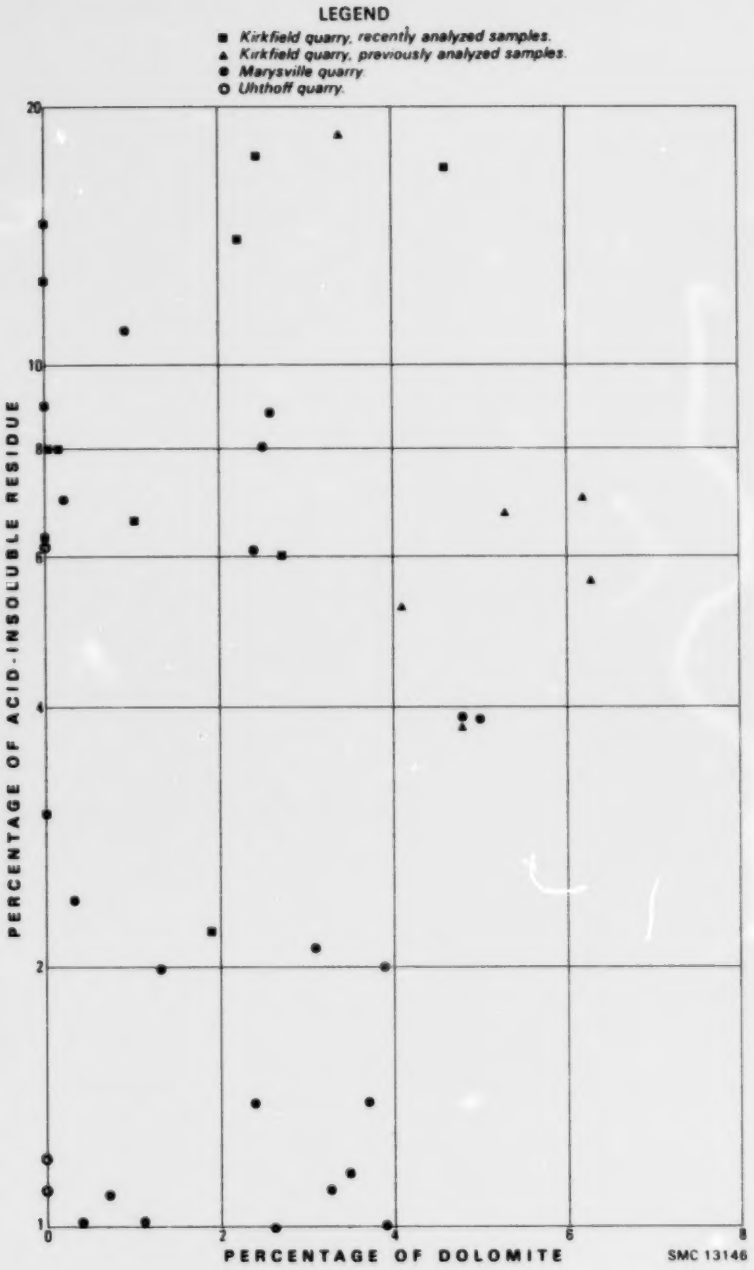


Figure 4–Basic composition of rocks from the Bobcaygeon Formation.

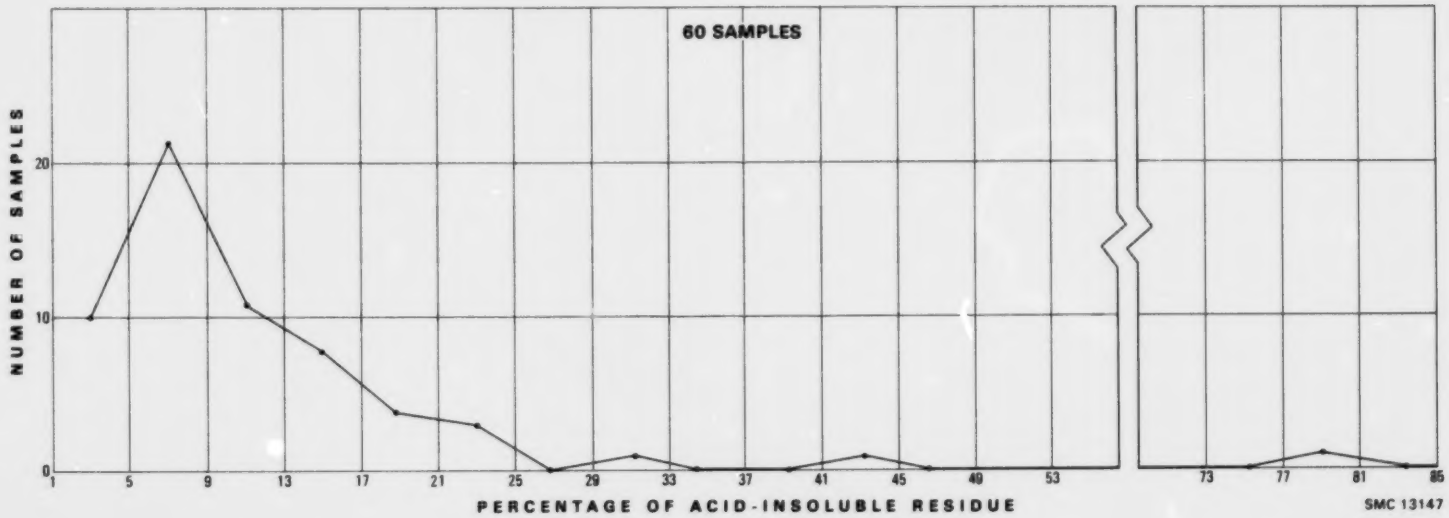


Figure 5A–Frequency distribution polygon of the percentage of acid-insoluble residue in rocks of the Bobcaygeon Formation from the Kirkfield quarry. The width of each class is 4 percent; the first class is 1 to 5 percent.

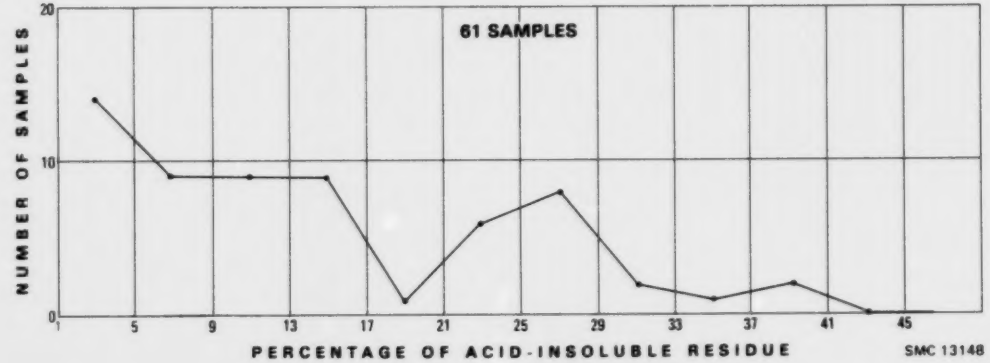


Figure 5B–Frequency distribution polygon of the percentage of acid-insoluble residue in rocks of the Verulam Formation from a construction site at Bath. The width of each class is 4 percent; the first class is 1 to 5 percent.

tions of stylolites with small changes in grain size of the intercalated carbonate rock. Slump structures are extremely rare (cf. Conybeare and Crook 1968).

CLASSIFICATION

The Bobcaygeon rocks from the Kirkfield quarry are pure to argillaceous, fossiliferous limestones, locally slightly dolomitized. According to the texture, they are biosparite to biopelmicrosparite with some varieties being fossil-bearing microsparite. Pelmicrosparite and biopelsparite are rare.

SUMMARIZED CHARACTERISTICS OF BOBCAYGEON ROCKS FROM THE KIRKFIELD QUARRY

The Bobcaygeon Formation in the Kirkfield quarry, used as the geological reference section for the Upper Member of the Bobcaygeon Formation (Liberty 1969, p.42), consists of interbedded, less frequently interlaminated limestone varieties with variable grain size in both the matrix and the cement, and containing variable amounts of fossils and pellets. These variations result in numerous specific rock-types but biosparite and biopelmicrosparite limestones are the most abundant rocks. The varieties range from relatively pure to distinctly argillaceous. Rocks classified as shales are rare because carbonate lamellae occur in the 'shaly' seams and rare interbeds, and lower the percentages of acid-insoluble residues. This does not prevent the development of distinct weakness planes along shaly concentrations. The rocks separate relatively easily along these films and seams, especially when weathered.

Chert accumulations are minute, normally rare and usually constitute much less than 1 percent of the rock. They form small inclusions in fossil fragments, and are not known to cause damage to concrete.

Marysville Quarry

Rocks from the Marysville quarry, located southeast of the Kirkfield quarry were examined to obtain additional information on the characteristics of the Bobcaygeon Formation. The quarry was operated on a 17-foot (5.2 m) face, when sampled. The upper third consists of thin to medium-thick beds, and the lower section of thick to medium beds.

SAMPLES

Twenty samples were taken by systematically sampling foot by foot from the top to the bottom of the face including a 3-foot (0.9 m) excavation ditch. The percentages of dolomite and the acid-insoluble residues were determined, and thin sections from all samples were examined.

HAND SPECIMENS

The rock is uniform in hand specimens, medium dark grey to medium grey (N4-5), and dark grey (N3) on surfaces covered with thin shaly films.

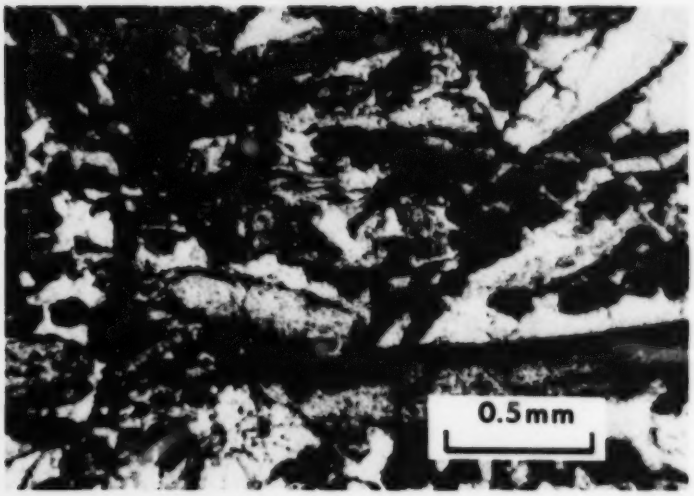
BASIC COMPOSITION

The basic compositions of the 20 samples are presented in Figure 4. The rocks are limestone very low in dolomite. Two thirds of the samples have less than 4 percent dolomite and less than 3 percent impurities. The average acid-insoluble residue is 3.4 percent with a range from 1.0 to 11.1 percent. Quartz and clay minerals were positively identified in the few samples containing more than 5 percent insoluble residue.

PETROGRAPHY

The thin sections show that this Bobcaygeon rock is a calcarenitic biopelsparite, and occasionally a rudite (Photo 11). The limestone contains abundant fossil fragments less than 1 mm in size and rarely more than 2 mm in size. A few macrofossils are oriented parallel to the layering. Rounded or oval micritic pellets of less than 0.1 mm diameter are abundant in the finely to coarsely crystalline cement. The pellets are not recognizable in hand specimens even using 50 times magnification, and the rocks appear uniformly aphanic (with a grain size below 0.2 mm) containing only macrofossils in a microsparry cement. Scarce silty quartz was observed in a few sections. Small areas are partially dolomitized; dolomitization usually destroyed the pellets and partially destroyed the fossils.

Several thin sections contain narrow wavy stylolites or thin black bands up to 0.03 mm in thickness coloured by organic matter. They consist of silty, clastic quartz grains in a matrix of calcite and clay minerals. The stylolites may branch into wider bands 2 mm or so in width which contain fewer fossils and



ODM9026

Photo 11–Marysville quarry, Bobcaygeon Formation; photomicrograph of pellet-bearing biosparite, showing 3 mm-long macrofossil in lower right quadrant. Photo by W. Hicks.

pellets than the average rock. In some places the stylolites narrow down for short distances to less than 0.01 mm in width and contain no quartz. A film of clay mineral concentrations was occasionally evident at the border of the silty bands.

CLASSIFICATION

The rocks are mostly calcarenitic biopelsparite, a relatively pure limestone, and are rarely argillaceous or silty.

SUMMARIZED CHARACTERISTICS OF MARYSVILLE ROCKS

The composition of the biopelsparite limestone is very uniform with low percentages of dolomite and acid-insoluble residues. Clastic quartz is a significant constituent of the residues and the amounts of clay minerals in the rock are very low.

The texture of the rock varies appreciably in grain size of the cement, fossil remnants and recrystallized fossils. Rare macrofossils are oriented parallel to the layering. The rocks are seldom coarse-grained, but sets of beds or individual beds below the quarry floor are more coarsely crystalline because of aggregations of coarse (up to 2.2 mm) calcite cement and fillings of former voids.

The quarry contains few thin beds, indicating that there are not many shaly interbeds or partings, and laboratory examinations of samples confirm this. The prominent shaly interbed in the upper part of the quarry was not examined but was not considered important because the amount of this rock in the quarry face was small, and the softer shaly material would be partially lost during processing. Several thin sections showed relatively high concentrations of organic matter.

Uhthoff Quarry

The three samples taken from the Bobcaygeon beds at the top of the Uhthoff quarry are microscopically and compositionally of the same type as those described above.

Comparison of Kirkfield and Marysville Rocks as Aggregates

A comparison of rocks from the Kirkfield quarry, which was developed mainly in the Bobcaygeon Formation, with those from the Marysville quarry, which is developed only in the Bobcaygeon Formation, is interesting. The Kirkfield rocks have a long history of performance as crushed aggregate. The similarities and differences which influence the qualities of aggregates from the two sources are as follows:

1–The Marysville quarry contains very uniform rock in the 17-foot (5.2 m) quarried section. The Kirkfield quarry had a depth of 36 feet (11.0 m) in the Bobcaygeon and 5 feet (1.5 m) in the Verulam, and contained a greater variety of rocks than the Marysville quarry.

2–The textures of the rocks are somewhat different in the two quarries; coarsely crystalline varieties

occur in the fossiliferous limestones in the Kirkfield quarry but are limited to beds below the floor in the Marysville quarry. Very coarsely crystalline grains in an aggregate have an adverse effect on the bond of rock particles to cement paste and, an abundance of large grains will adversely affect the strength of concrete.

3–The rocks in both quarries are low to very low in dolomite indicating that microstresses due to dolomization cannot be significant in the rocks.

4–The 20 thin sections from the Marysville samples did not contain chert, whereas some chert associated with fossils was found in crushed samples and thin sections of the Kirkfield rocks. Chert of this origin is not usually deleteriously reactive. In a modified sodium sulphate immersion test using two sets of 36 of ¾ inch (19 mm) to ⅜ inch (4.5 mm) particles, the set with visible chert inclusions gave a somewhat better result than the set without visible chert. There was only a 2 percent loss on a representative sample of crushed coarse aggregate from the Kirkfield quarry tested according to ASTM Designation: C88, "Standard Method of Test for Soundness of Aggregate by use of Sodium Sulfate or Magnesium Sulfate".

5–The mean acid-insoluble residue for the Marysville samples was 3.4 percent and a portion of this was quartz. The main acid-insoluble residue for 23 samples[1] from the entire Kirkfield quarry was 7.8 percent and the impurities were mostly clay minerals.

6–The Marysville quarry contains few clayey concentrations in the form of stylolites, seams, and partings, but it is evident from the basic compositions given in Figure 5A and from thin sections that distinctly argillaceous varieties were not rare in the Kirkfield quarry. Shaly stylolites are normally weakness planes but if they contain appreciable amounts of quartz, the undesirable effect of accompanying argillaceous concentrations is diminished.

7–The exact amount of organic matter in stylolites and clayey partings in rocks from the two quarries was not determined. Its effect on the quality of the rocks would have to be assessed. In the more or less pure limestones the amount is probably negligible.

The data indicate that there are significant differences in properties between the products from the two quarries in spite of the general similarity of the rocks. The aggregates from the Kirkfield quarry were classed as borderline quality rocks on the basis of various standard tests. The uniform, almost-pure limestones forming the face of the Marysville quarry indicate that good quality rocks are present in various locations of the Bobcaygeon Formation. Since Liberty (1971, p.5) states that the Formation is 20 to 30 feet (6.1 m to 9.1 m) thick in the east, the Marysville quarry may operate in almost the whole thickness of the Bobcaygeon Formation; the uniformity of the rock may very well typify the crushed products from the Bobcaygeon Formation in this area. The amount of such pure limestone available in the Kirkfield quarry, the geological reference section for Bobcaygeon, can no longer be established. The examinations that have been made do show that the variety containing distinct pellets, as found in the Marysville rocks (Photo 11), was rare in the crushed Kirkfield rocks.

On the other hand, the weathered top layers of the Bobcaygeon in the Uhthoff quarry, farther west than the Kirkfield quarry, consist of rocks similar in composition and texture to those in the Marysville quarry. Hand specimens of the rocks were not similar in appearance, but this might be due to weathering.

Verulam Formation

The Verulam Formation is the most distinct lithologic unit in the Simcoe Group. The Formation consists essentially of evenly bedded, fine-textured, bioclastic limestone alternating with distinct shale beds (Liberty 1971, p.16). The area of the Formation is shown on Chart A.

Representative Quarries

Between 32 and 35 feet (9.8 m and 10.7 m) of the Upper Verulam are exposed in the lower section of the Picton quarry. The overlying 50 feet (15.2 m) in the quarry is Lindsay Formation. At the bottom of the Ogden Point quarry 4½ feet (1.4 m) are probably Verulam (Liberty 1972, personal communication). Because this section is rather thick-bedded (see Photo 16) and because these near-the-bottom beds are similar to those found in the Lindsay Formation, the four samples from these beds are included in the discussion of the Lower Member of the Lindsay Formation.

[1] The 23 samples from the entire Kirkfield quarry consisted of 19 samples from the Bobcaygeon Formation and 4 samples from the Verulam Formation.

ODM9027

Photo 12–Picton quarry, showing thin-bedded limestone of the Verulam Formation (a on photo), Lower Member of the Lindsay Formation (b on photo), and Upper Member of the Lindsay Formation (c on photo). The total height of the quarry face, in two lifts, is about 100 feet (30 m). Photo by J. Mantuani.

Picton Quarry

The Verulam Formation in the Picton quarry consists of interbedded thin beds of limestone and shale (Photo 12). Almost 60 layers of limestone and shale can be recognized in the 12 to 15 feet (3.7m to 4.6 m) at the bottom of the quarry. This section of the quarry face is usually wet because it is probably below the level of nearby Lake Ontario. This may have caused the separation of the shaly parts from the purer limestone bands in some beds. The ratio of limestone to shale is about three to two. The maximum thickness of beds of each rock type is 3 inches (7.5 cm). The upper 18 to 20 feet (5.5 m to 6.1 m) of the Verulam Formation in the quarry have somewhat thicker limestone beds.

Hewitt describes this geological unit as consisting of "thin- to medium-bedded, medium-grey, aphanitic to medium-crystalline limestone and interbedded grey shale" (1960, p.27); and in part coquinoid calcarenite consisting of fossil debris (1960, p.50).

Kirkfield Quarry

The weathering of the Verulam beds may be observed in the Kirkfield quarry where they form the uppermost 5 feet (1.5 m) of the quarry face. Because these beds lie conformably on the Bobcaygeon beds, they belong to the Lower Member of the Verulam Formation, but their features are common to the whole Verulam Formation. The rocks are weathered to a brownish colour, olive grey (5Y6/1), and locally yellowish brown (10YR5/2). Weathering usually affects the clayey layers more than the limestone beds which often remain grey between the narrow brownish interbeds. Pieces taken from the deeply weathered beds separate easily along the bedding planes leaving the limestone wisps and lenses standing out as a wavy surface.

SAMPLES

Samples of 14 limestones and of 3 shaly interbeds were collected from the lower 30 feet (9.1 m) of the Picton quarry face; 4 samples of weathered limestones were taken from the top beds in the Kirkfield quarry. To further characterize the formation, acid-insoluble residues determined on 61 samples from a construction site in the lower Verulam near Kingston (at Bath) were used. Of these samples, 31 were crushed particles, 1½ inches to ¾ inch (37.5 mm to 19 mm) in size; 18 were taken at regular intervals from a 45-foot (13.7 m) long drill core; and 12 represent varieties of Verulam rocks distinguishable in drill cores.

HAND SPECIMENS

The 17 Picton samples were taken mainly from four horizons. A cursory inspection of the rocks in the quarry gives the impression that most beds are uniform, finely crystalline to aphanic rocks in which macrofossils are visible. A great variation in texture

is noticeable on cut surfaces of the samples, and even more in thin sections. The fresh rocks are medium grey to medium dark grey (N5-4), and dark grey (N3) in argillaceous stylolitic parts, shaly partings and seams which frequently contain rare whitish macrofossils. On weathering, the rocks become light grey (N7) due to the oxidation of organic matter.

BASIC COMPOSITION

The basic composition of the Verulam Formation is shown in Figure 6. Data from 17 Picton samples and 4 Kirkfield samples are plotted on the graph.

The graph shows that the amounts of dolomite are very small in all samples including the shales; the average is less than 1 percent. The insoluble-residue content varies appreciably in the Picton samples, from 3.8 to 24.3 percent in the limestones with an average of 11.2 percent, and from 57.6 to 69.5 percent in the shaly interbeds. The relatively high insoluble-residue content in three samples, from 19 to 24 percent, is due to stylolites, seams with gradational increase in argillaceous matter, and shaly partings attached to the samples. The very low content of acid-insoluble residues in the four weathered Kirkfield samples, from 1.2 to 3.1 percent, may be partly due to leaching of the clay minerals in the weathered near-surface beds. It is expected that the variation in the acid-insoluble residue would be greater if more samples were analyzed, but a compositional gap (from 25 to 55 percent insoluble residue in Figure 6) appears to exist between the argillaceous limestones and the shaly interbeds.

The statistical distribution of noncarbonate impurities in the Verulam rocks, caused by interbedding and interlamination of limestones and shales, is shown graphically in a frequency distribution polygon (Figure 5B) in which the precentages of acid-insoluble residues of 61 samples from Bath, near Kingston, are plotted. The graph shows a bimodal and asymmetrical distribution curve characteristic of limestones from the Verulam Formation. In addition to one peak at 3 percent acid-insoluble residue, it shows a second distinct, although lower, peak in the segment between 21 and 29 percent. If the insoluble data from the recently obtained 21 samples from the Kirkfield and Picton quarries are added to those from the 61 rock samples, the bimodal aspect of the polygon becomes even more pronounced.

Figure 5B illustrates that although very pure and slightly impure limestones are typical for the Verulam Formation, limestones rich in impurities are also abundant. One-third of the samples had more than 20 percent noncarbonates. They represent beds and sections containing limestone varieties rich in argil-

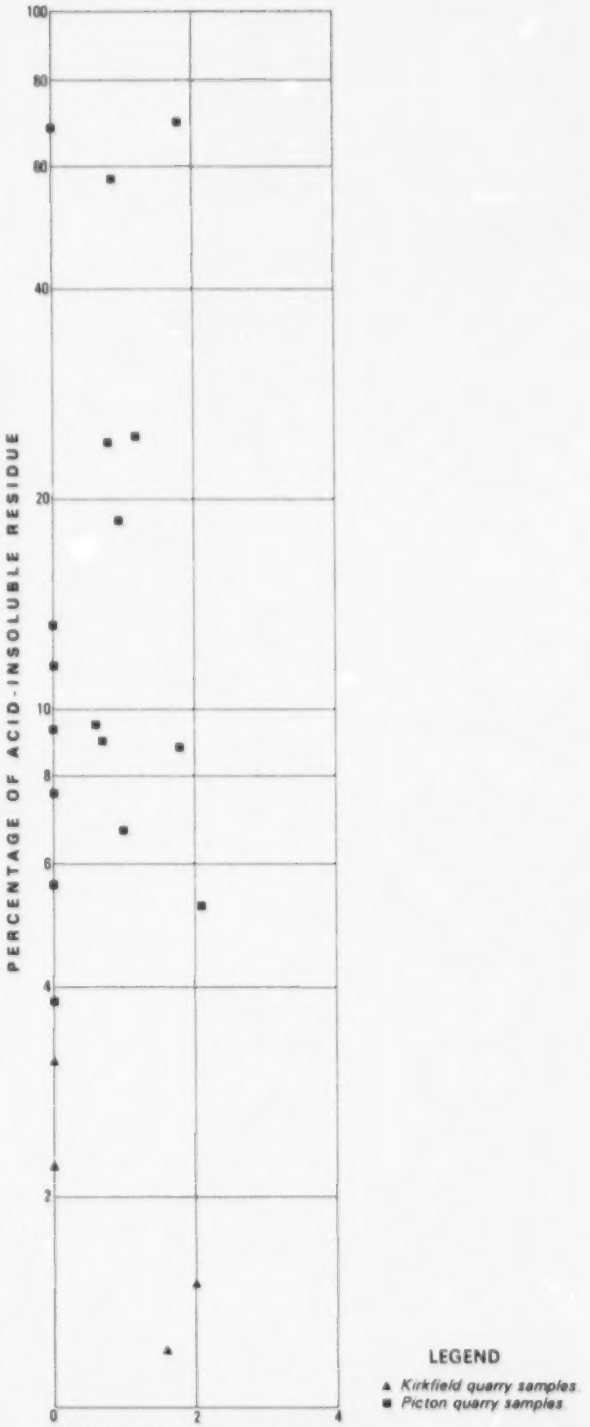


Figure 6–Basic composition of rocks from the Verulam Formation.

laceous material that is either finely distributed throughout the rock or concentrated in stylolites and seams. In the set of 61 samples from Bath, no sample contained more than 50 percent acid-insoluble residue even though 11 additional samples having the appearance of shale have been analyzed. However, three samples from the Verulam Formation in the Picton quarry did contain more than 50 percent residue and were classified as shales. The average amount of acid-insoluble residue of the Bath samples was 14.6 percent; this conforms with the value of 13.9 percent determined on two samples of crusher screenings obtained by crushing the drill cores from which 30 of the Bath samples were taken. Statistical evaluation of sample sizes of carbonate rocks (Dolar-Mantuani and Punhani 1974) shows, however, that results obtained on a quartered-down sample of crusher screenings (particles smaller than 4.7 mm) are normally significantly different from representative samples of crushed particles (coarser than 4.7 mm) or selected pieces taken from the same drill cores. This is caused by the fact that the argillaceous material tends to accumulate in crusher screenings but it is partially lost during the processing of crushed rock.

Figures 5A and 5B, representing the Bobcaygeon and Verulam rocks respectively, show the difference between these two Formations. Although rocks from both Formations are characterized by asymmetrical curves due to the presence of limestones very rich in noncarbonates, a second peak occurs in the curve for the Verulam rocks making this distribution curve bimodal. This is due to the presence of an argillaceous limestone type with about 25 to 30 percent noncarbonates. This rock type may be easily overlooked or mistaken for shale on cursory examination of drill cores or crushed samples.

MINERALOGY

The mineral composition was determined by thin section examinations and X-ray diffractometry analysis. The main constituent is calcite which occurs in the form of anhedral, coarsely crystalline to aphanocrystalline grains. There are slight differences between the types and relative abundances of the acid-insoluble (noncarbonate) minerals of the fresh Picton and weathered Kirkfield samples. Quartz occurs in all samples as a major constituent of the insoluble residue. Plagioclase is a minor constituent in the Picton rocks only, as is potassium feldspar in the Kirkfield rocks. Chlorite is present in moderate amounts more frequently than illite in the fresh rocks except for one argillaceous limestone sample in which illite is a major constituent of the residue. On the other hand, in the weathered samples illite seems to be better preserved than chlorite. Very minor amounts of an expanding mixed clay mineral are possibly present in half of the samples. Pyrite occurs in all fresh samples at least as a minor constituent of the residue. Gypsum was found only in samples from the Kirkfield quarry. Single grains of the brownish, isotropic phosphate *collophane* are visible in almost all thin sections.

PETROGRAPHY

Most of the thin sections of the Verulam limestones are abundant in fossil remnants. They are calcarenitic biosparites with interlamination of fossil detritus of different sizes and amounts, and finely crystalline to micritic intraclasts, as well as narrow laminae rich in either silty quartz or clay. The silty laminae show that quartz, which is usually a scarce and well disseminated constituent, locally forms a significant portion of the noncarbonate residue.

The megascopically uniform, aphanic limestone has a finely crystalline texture, contains fewer and smaller fossils than the biosparites and is commonly a microfossil-bearing microsparite (Photo 13). Enough pellets occur in some samples that contain fine calcarenitic fossils to classify the rock as pellet-bearing; the amounts are occasionally sufficient to classify the rock as biopelsparite. The organic structure of the fossil fragments is frequently well preserved. A few samples show later growth of coarse, sparry calcite grains having a regular outline typical of recrystallization (Photo 14). Some of these grains have central areas which include traces of organic structures. This texture is typical for the low-insoluble-residue varieties of the Upper Lindsay Formation.

Other textural types are rare in this unit. Two types that occur occasionally are: short clay-rich intraclasts aligned parallel to the layering of the limestone; and a nodular texture in argillaceous limestones similar to that in the turbidites which are frequent in the Lower Lindsay Formation (see the section "Petrography of the Lower Lindsay Member").

The almost-pure limestones of the weathered Verulam Formation in the Kirkfield quarry consist of interlaminated biosparite; some are pellet-bearing as in the Picton quarry. Signs of poorly winnowed micritic matrix and micritic intraclasts occur in a few samples.

The only thin section made from a fissile shaly interbed of Verulam rocks consists of an interlamination of an intraclast-bearing biosparite, 10 mm in thickness, intercalated between two laminae of calcareous, silty, quartzose shale (Photo 15). An interlamination of carbonate laminae and linear, clay mineral concentrations containing some carbonate constituents is a common feature visible in most thin

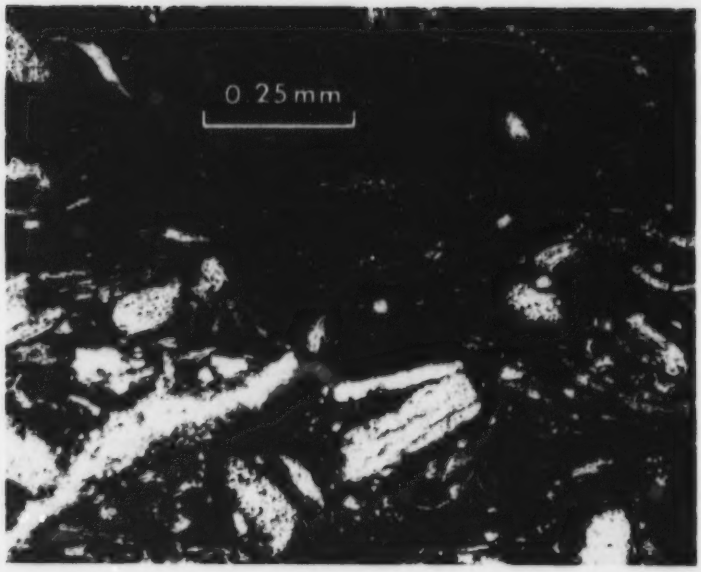


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Photo 13–Picton quarry, Verulam Formation; photomicrograph of argillaceous biomicrosparite with micritic intraclast (dark area in the upper part of the photo). Photo by W. Hicks.

ODM9029

Photo 14–Picton quarry, Verulam Formation; photomicrograph of biosparite showing finely to medium-crystalline, recrystallized sparry calcite with fossil remnants. Photo by W. Hicks.

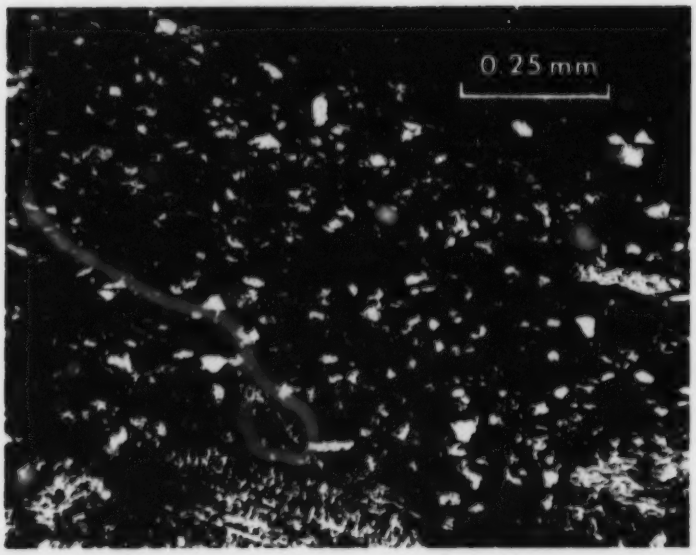

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Photo 15–Picton quarry, Verulam Formation; photomicrograph of interlaminated shaly interbed showing a lamina of biomicrosparite in the lower part of the photo, central lamina of silty, calcareous shale, and a shaly lens in upper right corner. Photo by W. Hicks.

sections of Verulam shaly beds and partings from other locations. The carbonate-rich laminae consist of single carbonate grains or groups of small grains enveloped in minute scales of clay minerals. Short lenses of pure clay minerals, along which the rock will easily crack, occur occasionally in the shaly laminae.

The dark grey colour of the clay-rich varieties is caused by organic matter in amounts up to 2.4 percent, mixed within the clayey concentrations.

CLASSIFICATION

The Verulam rocks are interbedded and interlaminated, pure to argillaceous limestones and calcareous shales. According to the texture and composition, they are calcarenitic biosparites, less frequently intrabiosparites, biopelsparites or microfossil-bearing microsparites. The latter rock grades into interlaminated calcareous shale in several beds.

Summarized Characteristics of Verulam Rocks

The most pronounced feature of the Verulam Formation is the interbedding of limestones and shales. The beds with shaly accumulations separate easily into thinner beds on weathering.

The most important compositional feature of the Verulam rocks is the very low dolomite content. The acid-insoluble residue, which is mostly clayey material, varies widely in amount, and the rocks range from very pure limestones to distinctly argillaceous varieties. No chert was detected in the Picton samples. Accessory minerals such as pyrite are rare, and gypsum, when present, occurs in trace amounts. The organic matter content is relatively high in some shaly accumulations.

The great variations in texture and composition are caused by frequent interlaminations on a microscopic scale. Textural and compositional variations are typical for the argillaceous aphanic varieties, shaly seams, and for shaly interbeds in which the clayey material is interlaminated with calcite. The fossiliferous limestones low in argillaceous material form thicker beds than the aphanic varieties but they frequently grade into argillaceous seams toward the top of the beds.

Properties of Verulam Rocks Relevant to Industry

The properties listed above, especially the low dolomite content, make the Verulam rocks suitable for cement production; their use in this industry is discussed in a later section "Properties of Rocks Used for Cement Production: Picton and Ogden Point Quarries".

Verulam rocks are seldom used for producing crushed rock and are usually unsuitable for producing concrete aggregate because the rock tends to break into flat pieces and because clay concentrations in

ODM9031

Photo 16–Ogden Point quarry, showing the thin-bedded Upper Member of the Lindsay Formation overlying the medium- to thick-bedded Lower Member of the Lindsay Formation. The quarry face is about 100 feet (30 m) high. Photo by J. Mantuani.

some beds tend to make the rocks soft. Many of the beds in this Formation gradually change from pure, compact limestone to shaly seams and partings. It is impossible to produce high quality crushed rock from these beds without losing satisfactory material even if heavy liquid separation is used. The results of sodium sulphate tests (ASTM Designation: C88) on this rock, showed losses from 11.6 to 14.1 percent for samples containing an average of 14.6 percent acid-insoluble residue. Shaly seams of Verulam limestone have poor freeze-thaw resistance and "peel off" on weathering. Shaly particles embedded in concrete near the surface tend to cause popouts. In view of these results, the production of coarse concrete aggregate was discontinued at the Picton quarry years ago.

Some sections of the Verulam Formation may be suitable for producing rock for roads or even for concrete aggregate if the shaly beds can be stripped away leaving adequate sections of limestone that is low in argillaceous impurities.

Lindsay Formation

Liberty (1963, p.10-11; 1960b, p.5) divided the Lindsay Formation into two members: the Lower and Upper Members. The Lower Member is a very finely crystalline to subcrystalline limestone that weathers to thin, pseudo-nodular beds. The Upper Member is a grey, calcareous clay-stone which weathers into irregular, rubbly and nodular beds enclosing thin shaly partings. It also contains thin beds of a grey finely crystalline, bioclastic limestone.

Hewitt (1960) classified the Lower Lindsay rocks as upper Hallowell and described them as medium bedded, slightly argillaceous limestones with shaly partings which become thinly bedded on weathered surfaces. He described the Upper Lindsay Member, which is the Hillier Member of the Cobourg Formation according to the biostratigraphic classification of Kay (1937 *in* Hewitt 1960, p.27) as irregularly bedded with conspicuous banding due to layers of two rock varieties, one being a coarse coquinoid calcarenite and the other an argillaceous to slightly-argillaceous limestone.

Picton and Ogden Point Quarries

Both Lindsay Members occur in the Picton and Ogden Point quarries. In the Picton quarry, the Lower Member forms a 50-foot (15.2 m) section overlying the Verulam beds in the lower part of the quarry. The brownish-weathered beds, occurring in a 12- to 15-foot (3.7 m to 4.6 m) section at the top of a portion of the quarry (see Photo 12), are most probably the Upper Lindsay. The Ogden Point quarry is worked in the Lindsay Formation, possibly including a few Verulam beds at the bottom (cf. section "Verulam Formation"). About 60 feet (18.3 m) are in the Lower Member, and 40 feet (12.2 m) in the Upper Member (Photo 16).

In both quarries the Lower Lindsay Member consists of relatively thick beds, one to several feet in

thickness, containing seemingly uniform, compact limestones with shaly partings. Beds of this thickness are evident on the faces of joints, but much thinner beds are apparent in blasted areas and on weathered surfaces of the quarries.

In the Ogden Point quarry, beds in the Upper Lindsay Member have the megascopic appearance of a shaly limestone separated by thinner shaly interbeds. The interbeds are 5 to 7 inches (12.5 to 18 cm) in thickness. The thicker beds, ranging up to 3 feet (0.9 m) in thickness, consist of bands and lenses of a fossiliferous limestone interlayered with apparent shaly bands, 1 to 2 inches (2.5 to 5 cm) in thickness. The interlayering of these rocks is recognizable in slightly weathered blocks where differences in grain size and colour are evident. The argillaceous varieties, occurring in bands and interbeds, seem to be more abundant than the coarser grained fossiliferous varieties that are more conspicuous. The surfaces of shale-rich partings on beds and bands have an uneven nodular texture indicating that lenses, nodules and irregular wide bands are different in composition and texture.

The differences between the medium-grained nodules, wisps and lenses, and the more uniform partially fissile shaly layers, are very pronounced in the brownish-weathered beds of the uppermost portion of the Picton quarry.

SAMPLES

The quarries were sampled to obtain megascopically distinguishable varieties. Thirteen samples were from the Lower Lindsay Member: six from the Picton quarry and seven from the Ogden Point quarry; twenty-six samples were examined from the Upper Lindsay Member: sixteen from the Ogden Point quarry, and ten from the weathered top beds in the Picton quarry. Only four of the weathered Picton samples had the basic compositions determined and thin sections made.

HAND SPECIMENS

The Lower Lindsay rocks are more or less evenly bedded and contain narrow shaly partings at the tops of the beds. Detailed examinations show that nodules of fossiliferous limestone separated by areas rich in argillaceous material are typical of the Lower Lindsay Member. Large variations in the shape, size and distribution of the nodules are visible on cut surfaces. The maximum diameter of a nodule observed was 65 mm but smaller sizes were more frequent. The nodules are round, oval, or irregular. In several samples the nodules are homogeneous, finely crystalline and do not contain macrofossils. The nodules are separated by one or more stylolites, or by wider argillaceous bands. A few macrofossils occur in the stratified areas between the nodules.

The Upper Lindsay samples are narrow, 1.5 to 5 cm in width, indicating that the samples represent mainly the narrow beds that predominate in the quarry face.

Three limestone varieties are recognizable in the samples. The aphanic and homogeneous rocks are most abundant and can be divided into two varieties, (a) a slightly fissile limestone that contains some parallel shaly concentrations, and (b) a randomly textured limestone that breaks conchoidally. The latter variety may grade into the fissile variety or into darker grey shaly seams. These gradational bands frequently contain some whitish macrofossils. Several beds of the slightly fissile limestone are interstratified with a third variety, (c) a medium-crystalline fossiliferous limestone that occurs in lenses and bands of irregular thickness and is characterized by an abundance of broken shells and other fossil detritus. This variety is the least abundant in the Upper Lindsay Member. Lenses and wisps of the fossiliferous limestone, and the macrofossils within the otherwise aphanic varieties give a nodular appearance to the surfaces of many beds.

Fresh rocks from the Lindsay Formation are medium to medium-dark grey (N5-4). The argillaceous stylolitic parts and shaly partings are dark grey (N3) or, more frequently, light grey (N7) because of slight weathering. On distinct weathering the argillaceous concentrations of the Upper Member show a greenish tint (5G6/1) in the Ogden Point quarry while they are moderate brown (5YR4/6) in the upper weathered portion of the Picton quarry. There, the argillaceous limestone is pale to dark yellowish brown (10YR 7-4/2) depending on the amount of dusty limonite inclusions; but the rock portions rich in fossils are grey on freshly cut faces, proving that the degree of weathering is much lighter in the brownish beds of this quarry than field observations suggest.

BASIC COMPOSITION

The basic composition of the 33 samples from the Picton and Ogden Point quarries representing the Lower and the Upper Members of the Lindsay Formation are given in Figure 7. The compositions of the Verulam samples from the Picton quarry are also given in Figure 7 for comparison. The following conclusions have been drawn from the graph:

1. The percentages of dolomite are very low in all rocks from the Lindsay Formation;

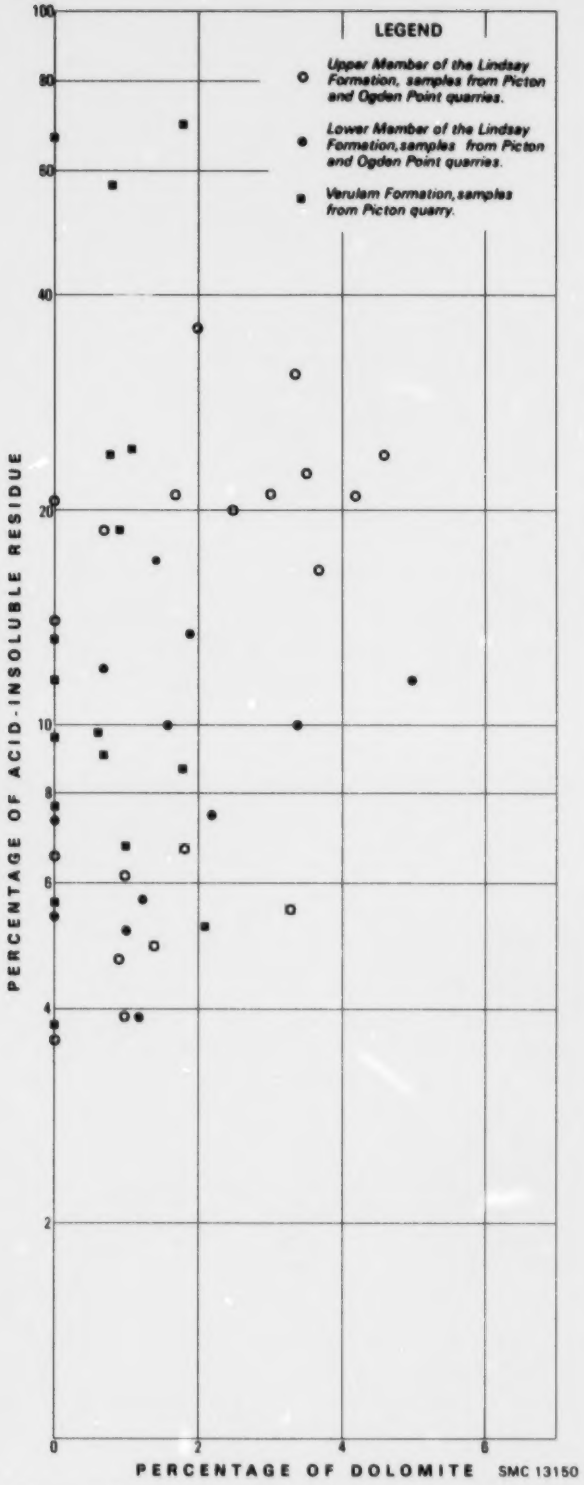

LEGEND
Upper Member of the Lindsay Formation, samples from Picton and Ogden Point quarries.
Lower Member of the Lindsay Formation, samples from Picton and Ogden Point quarries.
Verulam Formation, samples from Picton quarry.
PERCENTAGE OF ACID-INSOLUBLE RESIDUE
PERCENTAGE OF DOLOMITE
SMC 13150

Figure 7–Basic composition of rocks from the Lindsay Formation; the composition of Verulam rocks from the Picton quarry (from Figure 6) are shown for comparison.

they vary from traces to a maximum of 5 percent.

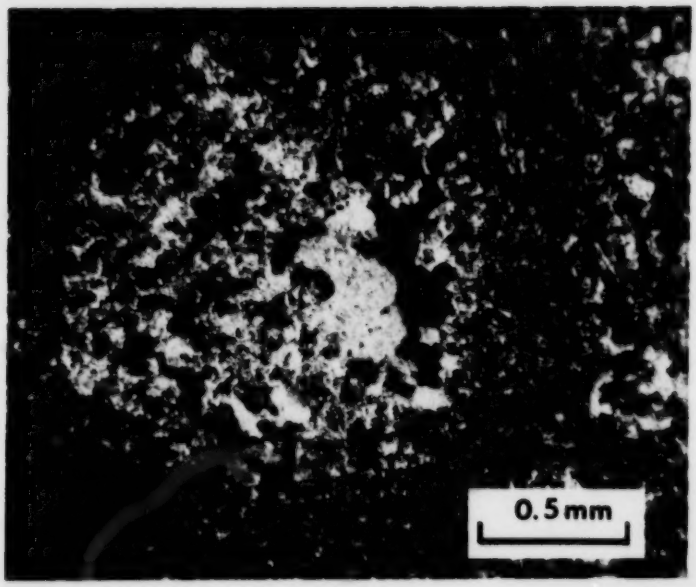
2. The percentage of acid-insoluble residues varies appreciably but is always less than 50 percent, so none of the samples can be classified as shale. The maximum amount of insoluble residues in the Lower Lindsay samples is 17 percent which is significantly lower than in the Upper Lindsay for which the maximum is 36 percent.
3. Relatively pure limestones with less than 8 percent insoluble residues and less than 3.5 percent dolomite are present in both members.
4. The 13 samples from the Lower Member are distributed within the range from 4 to 17 percent residues while a gap seems to exist in the Upper Member between the limestone varieties with less than 7 percent insoluble residues, and the argillaceous and (or) sandy limestones with 14 to 36 percent residues.

MINERALOGY

The mineral composition was determined by thin section examinations and by X-ray diffractometry. The main constituent of the rocks is calcite which occurs in the form of anhedral, coarsely crystalline to aphanocrystalline grains. Occasional rhombohedrons of dolomite are visible in a few intraclasts in several thin sections.

The X-ray analysis shows that quartz is the main component of the acid-insoluble residues, but thin sections of several argillaceous samples indicate that there are more clay minerals than silty quartz grains in some beds. The three clay minerals identified in decreasing order of abundance are chlorite, illite, and an interstratified expanding clay mineral within illite. Illite is either absent or present in traces in limestones containing small amounts of acid-insoluble residues, but it occurs as a minor constituent in the residue of almost all argillaceous varieties. Only chlorite was identified in fresh samples with less than 5 percent insoluble residues; in weathered samples with the same percentage of insoluble residues, illite was also present.

According to X-ray examinations, feldspars occur in almost all samples as minor constituents of the insoluble residues. Plagioclase proved to be more abundant than potassium feldspar which occurred in traces only and was absent in the weathered samples from the Upper Member. Feldspars were, however, not



ODM9032

Photo 17–Ogden Point quarry, Lower Member of the Lindsay Formation; photomicrograph of a turbidite-intraclast consisting of a biosparite core (coarser-grained material at centre of photo) surrounded by a rim of microsparite (finer grained material); the calcarenitic biosparite surrounding the intraclast is seen at the extreme right of the photo. Photo by W. Hicks.

identified in any of the 33 thin sections made from Lindsay rocks.

Cubes of pyrite were visible in several samples but according to the X-ray analysis, pyrite was present in traces only. Lee and Winder (1967, p.533) report pyrite as the most common authigenic mineral in the rocks from the Ogden Point quarry. They observed sand-sized cleavage fragments of orange sphalerite in the residue of some Lindsay rocks. Because the weathered rocks are brownish, iron sulphide is undoubtedly present, especially in the argillaceous portions; but extremely small amounts of limonite, the weathering product of the iron sulphides, may produce distinct discolouration. Opaque spheres of organic matter were visible in several thin sections.

PETROGRAPHY OF THE LOWER LINDSAY MEMBER

The nodular texture observed on cut surfaces of the Lower Lindsay rocks is usually emphasized in thin sections. The nodular intraclasts show a great variation in shape and grain-size of calcite, and in the presence or absence, and type of fossils. The intraclasts are lens-like, oval or rounded; they consist of microsparite with or without fossils, or less frequently, they are medium-crystalline biosparite very low in noncarbonate impurities. In the biosparite, the fossils are recrystallized to sparry calcite; they are either calcarenitic in size or macrofossils measuring more than 1 mm in length or diameter. The cement between the fossils and the filling in former voids and openings are also sparry calcite.

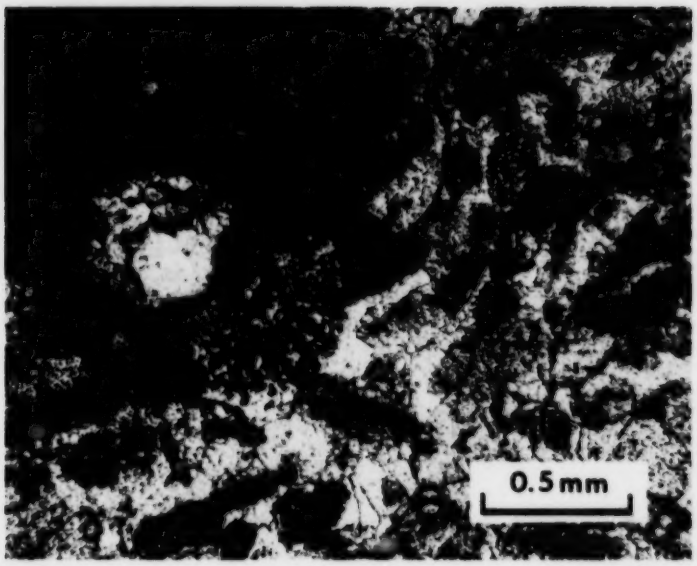
The fossil remnants of some intraclasts form a circular pattern indicating rotation of the intraclasts; such texture is typical of turbidites. A rounded center of a turbidite formed by biosparite and rimmed by microsparite is shown in Photo 17. Harlett and Kulm (in press) described recently that near bottom current measurements generally demonstrate a rotary motion with a net offshore flow (Komar, Kulm, and Harlett 1974).

The matrix separating the intraclasts differs from them in composition and texture. The matrix is usually more argillaceous and more finely crystalline than the intraclasts and contains repeated stylolites. In some varieties the matrix is more abundant and relatively rich in clay minerals, or smaller microsparry intraclasts are interspersed in large areas of calcarenitic biosparite. In other varieties the aphanocrystalline matrix between the fossils was poorly winnowed, producing pseudoclasts.

Samples of a nodular biosparite with less pronounced stylolitic areas between the nodules are low in insoluble residue. In a few samples dolomite has replaced the calcite in the intraclasts but not in the remainder of the rock. Silty quartz is present in a few samples in addition to clayey material.

Classification

The megascopic, relatively uniform, nodular texture of the Lower Lindsay in which the nodules form



ODM9033

Photo 18–Ogden Point quarry, Upper Member of the Lindsay Formation; photomicrograph of biosparite with micritic remnant. Photo by W. Hicks.

the dominant portion of the rocks, causes great variations in textural detail, which makes it difficult to classify the Lower Lindsay rocks precisely. In general, they are fossiliferous, pure to impure limestones which may be stylolitic, argillaceous, and slightly quartzose. Considering the texture, the rocks are fossil-bearing intramicrosparites, biomicrites and biosparite-turbidites.

PETROGRAPHY OF THE UPPER LINDSAY MEMBER

The most typical feature of the rocks from the Upper Lindsay Member is interbedding, interlayering, and interlamination of limestone varieties. The laminae vary in composition, being either pure limestone or an argillaceous variety with or without a significant amount of silty quartz. They vary in the amount and size of fossil remnants, and in texture. The limestone has a grain size range from aphanocrystalline to coarsely crystalline.

The most prominent varieties are homogeneous, fossil-bearing limestones of microsparite or algal micrite types, and finely to medium-crystalline, fossiliferous, relatively pure biosparite limestones. The biosparites are characterized by great variations in the sizes of fossils, calcite cement grains, and finely crystalline intraclasts. The intraclasts may be remnants of a poorly winnowed matrix, or they may be typical algal intraclasts. The fossils are usually fine-calcarenitic, partially recrystallized to form sparry calcite grains with straight outlines (Photo 18), or less frequently macrofossils up to 4 mm in size. The biosparite may be recrystallized to an average grain size of 0.5 mm. A few biosparites are pellet-bearing or contain micritic to microsparry intraclasts which are dolomitized.

The argillaceous limestones, which have a shaly appearance in hand specimens, contain finely distributed clay minerals or repeated stylolites with or without silty quartz grains. The argillaceous limestones with microfossils and sparse to abundant macrofossils in a microsparry matrix, grade locally to shaly seams. The interlamination of the megascopically aphanic rock varieties, such as argillaceous micrites and microsparites, with few fossils, or without fossils, is visible in thin sections; the biosparite varieties usually form wider laminae.

The appearance of the upper brownish-weathered limestone beds in the Picton quarry leaves some doubt as to whether they belong to the Lower or Upper Lindsay Member. They were included in the Upper Member because of the abundance of narrow, distinctly fissile, argillaceous layers and bands between the biosparites and the biomicrites with few macrofossils; these layers and bands are similar to the argillaceous layers in the Upper Lindsay Member at other locations.

Classification

The Upper Lindsay Member consists of interbedded and interlaminated fossiliferous limestone and

more abundant argillaceous limestone with or without fossils. According to the texture, the interlaminated rocks are fossil-bearing microsparites and biosparites; the argillaceous limestones are micrites to microsparites which may be silty quartzose.

Summarized Characteristics of Verulam and Lindsay Formation

COMPOSITION

An overall picture of the composition of the rocks quarried for cement is given by separating the rocks of the three stratigraphic units, the Verulam Formation and the Upper and Lower Lindsay Members, into two groups: rocks containing less than 10 percent noncarbonate impurities and rocks containing more than 10 percent of them. The results are shown in Table 3 and are illustrated in Figure 7.

The average percentages of the noncarbonates and calcite are distinctly different for both types of limestone in each unit. It was also found that in each unit analysed the range of these two parameters did not overlap. The average basic compositions of the relatively pure limestones are the same for all three stratigraphic units. The average amount of noncarbonates in the impure limestones is highest for the Upper Lindsay Member and lowest for the Lower Lindsay Member. The Verulam limestones are intermediate, but some shales were present among the samples analysed.

TEXTURE

The most characteristic textural features of the three stratigraphic units are interbedding and interlamination of limestone varieties in the Verulam Formation and in the Upper Lindsay Member; the Lower Lindsay Member is characterized by the presence of turbidites among the intraclasts. The textural complexity of the rocks on a microscale is revealed in thin sections showing that rocks with the same basic composition may be very different in microtexture.

Characteristics of Limestones for Cement Production

To produce portland cement that meets modern exacting requirements and specifications, the raw material used for cement manufacture must be uniform in composition and texture, and must have suitable chemical and physical properties. The raw material is usually a blend consisting mainly of limestone together with smaller amounts of material such as clay, shale and iron oxide. The exact blend depends upon the composition of the raw materials available and economic considerations. Limits specified for individual constituents of the raw material are only guidelines because the overall suitability must be determined on the basis of the entire mix. The requirements for the carbonate rock used for cement production deal with the composition, texture and structure of the rock.

Table 3 | BASIC COMPOSITION OF UPPER MIDDLE ORDOVICIAN ROCKS

STRATIGRAPHIC UNIT ROCK VARIETY	AVERAGE PERCENTAGES			NUMBER OF SAMPLES
	NONCARBONATE	CALCITE	DOLOMITE	
Upper Lindsay Member				
Limestone, less than 10% noncarbonate	5	94	1	8
Limestone, more than 10% noncarbonate	22	75.5	2.5	12
Lower Lindsay Member				
Limestone, less than 10% noncarbonate	6	93	1	6
Limestone, more than 10% noncarbonate	12	85.5	2.5	7
Verulam Formation				
Limestone, less than 10% noncarbonate	7	92	1	9
Limestone, more than 10% noncarbonate	18.5	81	0.5	5
Calcareous shale	65	34	1	3

COMPOSITION

According to L. E. Halsted[1] (1974, personal communication) argiliaceous limestones tend to vary in composition and therefore require more sampling and analysis to obtain the correct mix. Purer limestones tend to be more uniform in composition and therefore it is easier to blend and control the raw mix.

Suitable carbonate rocks are low in magnesium oxide, alkalis and specific impurities. The limits on magnesium oxide are stringent. The magnesium oxide in portland cement is highly detrimental, if due to improper cooling of the clinker, it occurs in the crystalline form as periclase which is slow to hydrate and causes expansion of the concrete. The limit of 5 percent magnesium oxide in ASTM Designation: C150 was adopted before a satisfactory performance test was available. The autoclave test (ASTM Designation: C151)[2] with its limits of 0.8 percent expansion provides a self-limiting value for the permissable magnesium oxide in portland cement. The actual magnesium oxide values will depend upon individual manufacturing processes and on the composition of the raw materials. It is necessary to carefully control the MgO content to meet the autoclave requirements. Autoclave unsoundness of portland cement is caused by free lime and (or) periclase (Halsted 1974, personal communication).

The presence of alkali-reactive carbonate rocks in the Gull River Formation (see Appendix II) and of alkali silica reactive rocks in the Canadian Shield (Dolar-Mantuani 1969a; 1971b) create a need for some low alkali cement in Ontario. The maximum allowable amount of alkali in portland cement to be used with alkali silica reactive aggregates is 0.60 percent, and for excessively expansive carbonate rocks the maximum is 0.40 percent; in both cases the total alkali is expressed as equivalent sodium oxide (Na_2O). These limits may change considering the influence of concrete mixture properties (see Appendix II, "Alkali-Reactive Carbonate Rocks"). Ontario cement plants normally produce high alkali cements containing about 1 percent sodium oxide equivalent. The alkalis occur in the clayey concentrations in the limestones, and in shales and similar rocks used for blending. The limestones usually contain less alkalis than the clays and shales. As the efficiency of the burning process increases, the retention of the alkalis also increases.

The impurities in the raw material may be very harmful although they may be present in minor or trace amounts. A list of minerals which affects either the quality of the cement or the burning process, based mainly on Pollitt's information (1964, p.33-35), includes fluorides, chlorides, sulphides such as sphalerite, galena, chalcopyrite and pyrite, and phosphates.

FABRIC

Materials which are not harmful but which influence the grindability of the raw material and the particle size range, are inclusions of chert and relatively large quartz grains. The grain size of the limestone also affects the particles size range in the raw mix. The hardness influences the fineness of the ground mixture and thereby the intimacy of contact of different constituents during the burning process (Pollitt 1964, p.31). Larger particles of silica or lime may produce local excesses or deficiencies of one component, thereby preventing a satisfactory combination of oxides in the kiln.

Clay impurities in a limestone are preferable to quartz and feldspar because the former are softer and produce a more uniform particle size. Compact, hard pure limestones are in general less desirable than softer limestones because they increase the cost of grinding (Lea 1970, p.133). Both the maximum grain size and the uniformity of grain size in the raw material are therefore important.

These general guidelines about the properties of limestone used for cement production are not adequate to define the composition and grain size required for a kiln feed. To develop a quarry for cement production requires a much more detailed program of petrographic examinations, sampling and analysis (Robinson and Gertiser 1964; Berry 1970).

Properties of Rocks Used For Cement Production: Picton and Ogden Point Quarries

For this study, representative samples of the rock varieties in the Picton and Ogden Point quarries, were collected for petrographic analysis of rocks used for cement production. Thus, mineralogical data given, including the basic composition are for these samples only; no attempt was made to determine average chemical composition of the quarries or deposits. The petrographic analyses do, however, give some infor-

[1] Director of Research, Ash Grove Company, Kansas City.

[2] In the autoclave test the soundness of portland cement is determined by measuring the expansion of the cement paste which takes place during exposure to high pressure steam for a defined period of time.

mation about chemical composition and texture which is summarized as follows:

1. All beds sampled in both quarries are low in dolomite. A maximum of 5 percent was found in one sample, and this is equivalent to about 1 percent magnesium oxide. Because the other beds contain even less dolomite, the average magnesium oxide is assumed to be very low. Some magnesium is present in the chlorite-type clay mineral.

   The process control analyses on the Ogden Point limestones gave an average of 1.9 percent magnesium oxide (MacDonald 1973, personal communication). This suggests that there may be some beds containing more dolomite than those sampled for the petrographic analyses.

2. The amounts of noncarbonates in the petrographic samples varied from 3 to 70 percent whereas process control analyses give a minimum calcium carbonate content of 77 percent for the Ogden Point rocks (MacDonald 1973, personal communication). This is lower than the petrographic results (see Table 3) because the argillaceous interbeds were not sampled in proportion to their frequency of occurrence, but only to obtain samples of the various rock types.

3. Sulphides were the only potentially harmful noncarbonate minerals observed in both quarries. Pyrite was recognized in the samples but according to X-ray diffractometry, it is present in trace amounts only. Sphalerite which was reported to be present (Winder 1964 *in* Lee and Winder 1967, p.533), was not found but the number of samples taken for the petrographic study was considerably smaller than the number taken for the fabric study by Lee and Winder. There is no indication in the petrographic samples that significant amounts of sphalerite or other sulphides are present as in the Silurian rocks farther west (Guillett 1967).

4. Textural analyses show that the finely crystalline, argillaceous limestones and argillaceous-rich interbeds have a satisfactory texture. The fossiliferous limestones are less desirable because of their coarser crystallinity and abundant macrofossils in some beds. These limestones are harder and more dense than the argillaceous varieties, and the macrofossils are harder than the microcrystalline matrix in which they are embedded. These rocks, when used for cement production, are more difficult to grind to a uniform and satisfactory particle size. Processing costs are therefore increased.

5. Most of the Verulam and Lindsay argillaceous rocks contain concentrations of clay minerals in the form of stylolites, seams and lenses, all of which represent weakness planes along which the rocks separate easily. This facilitates processing of the rock.

6. The harder fossiliferous variety of limestone is remarkably similar in all three stratigraphic units present in both quarries (see Table 3). The number and thickness of such beds may, however, vary. The argillaceous varieties show some differences in the three stratigraphic units but the differences are not considered to be significant for cement production.

To summarize, the petrographic data show that the rocks in both quarries are very low in magnesium oxide and that the rocks on processing produce a finely ground product which is reasonably uniform in composition and is satisfactory for cement production. The location of the quarries on Lake Ontario is advantageous for low cost transportation of blending material, fuel and the finished product.

The numerous interbeds, partings and clayey concentrations form weakness planes making the rocks unsuitable for producing concrete aggregates.

Summary of the Basic Composition of Simcoe Group Rocks

The six quarries selected to represent the Simcoe Group are listed in Table 4 together with the Formations and Members in each quarry. The average composition (the acid-insoluble residue, calcite and dolomite) of all samples taken from each quarry is also given.

Although average compositions have some serious limitations in characterizing a quarry containing rocks that are heterogeneous in composition, the table shows several interesting compositional features. The most striking is the difference between the Pittsburg quarry and the other five quarries. Only the Pittsburg quarry contains, on the average, more dolomite than calcite, in other words more dolostones than limestones. On the other hand, the amounts of dolomite are very low in the Uhthoff quarry which is also developed in the Gull River Formation. Most of these

Table 4 BASIC COMPOSITION OF ROCKS FROM SIX QUARRIES IN THE SIMCOE GROUP

QUARRY	FORMATION	AVERAGE PERCENTAGE		
		INSOLUBLE RESIDUE	CALCITE	DOLOMITE
Pittsburg	Gull River Member A	13	38	49
Uhthoff[1]	Gull River Members A, B, C	6	91	3
Marysville	Bobcaygeon	3.5	94	2.5
Kirkfield[2]	Bobcaygeon, Verulam	8	90	2
Picton	Verulam, Lindsay	10.5	88.5	1
Ogden Point	Verulam (?), Lindsay	14.5	83.5	2

[1] The uppermost 2 feet (0.6 m) are Bobcaygeon rocks.
[2] The Kirkfield quarry is now flooded.

limestones contain very little dolomite, and the dolostones present in Member A do not significantly increase the average quantity of dolomite present. The dolostones and limestones are interbedded throughout all three lifts of the Pittsburg quarry, while in the Uhthoff quarry dolostones occur in the lower lift only.

The average basic compositions for the other four quarries are similar. All are apparently very low in dolomite, although the detailed examinations show that the dolomite content may reach 17 percent in single beds in the Kirkfield quarry.

Slight differences in the acid-insoluble residue content are apparent for the quarries. The differences are more evident when considering the means and ranges for the insoluble residues shown in Table 5.

The percentages of acid-insoluble residues are not exact criteria for indicating the quality of the rocks, but the residues show the purity of carbonate rocks and therefore give some indication of the quality. The amounts of clay minerals, chert, quartz, and feldspars are better parameters for assessing carbonate rocks for various uses such as skid resistant aggregates. While clay minerals are particularly harmful when carbonate rocks are used as aggregates in portland cement or bituminous concretes on highways because of the low abrasion resistance of argillaceous carbonate rocks, the hard silicate constituents increase the abrasion resistance of the rocks. Gray and Renninger (1966) found that the ultimate skid resistance of a given carbonate aggregate varies directly with the percentage of acid-insoluble, sand-size material in the carbonate rock.

Table 5 PERCENTAGES OF ACID-INSOLUBLE RESIDUE IN SIMCOE GROUP ROCKS

QUARRY, LOCATION	PERCENT ACID-INSOLUBLE RESIDUE					NUMBER OF SAMPLES
	MEAN	STANDARD DEVIATION	95% CONFIDENCE LIMIT UPPER	95% CONFIDENCE LIMIT LOWER	OBSERVED RANGE	
Pittsburg	12.8	10.2	15.9	9.7	1.5 – 49.1 (52.6)	42 (1)
Crusher dust	19.5	...	...	...	...	1
Uhthoff	6.2	7.2	8.6	3.8	0.8 – 33.8 (61.2, 64.7)	35 (2)
Marysville	3.4	3.1	4.8	2.0	1.0 – 11.1	20
Kirkfield	7.8	5.3	9.9	5.6	1.2 – 18.5	23
Previous samples	10.8	7.6	12.7	8.9	1.4 – 43.3 (78.9)	59 (1)
Construction site at Bath						
Previous samples	14.6	10.3	17.2	12.1	2.0 – 39.2	61
Crusher dust	13.9	...	...	...	13.5, 14.2	2
Picton	10.6	6.2	13.0	8.1	3.6 – 24.3 (57.6, 67.5, 69.5)	24 (3)
Ogden Point	14.5	9.1	18.2	10.7	3.9 – 36.1	23

The values given in brackets in the range column are those for silicate rock samples not included in the means.
Formations occurring in the quarries are listed in Table 4. Construction site at Bath is in the Verulam Formation.

SUMMARY

The Middle Ordovician Simcoe Group, consisting mainly of limestones and very subordinately of dolostones, is divided into four lithologically different Formations, the Gull River, the Bobcaygeon, the Verulam, and the Lindsay.

To determine the lithology of the four Formations, six quarries were analysed in detail, namely Pittsburg, Uhthoff, Kirkfield, Marysville, Picton, and Ogden Point. The locations of the quarries and the areas in which the four Formations outcrop are shown on Chart A.

The Gull River Formation, which is the oldest of the Group, has by far the greatest lithological variation. This is particularly evident in eastern Ontario around Kingston where the Formation consists of four Members, A, B, C, and D. Farther west, around Orillia, the Formation consists of only three Members, A, B, and C. In the west, dolostones occur only in a 9-foot (2.7 m) section of Member A but in the east, dolostones are more abundant than limestones in Member A and they occur interbedded with the limestones. The younger Members, examined in the west only, contain more or less pure limestones with the exception of one unit at the bottom of Member B which is an argillaceous dolomitized limestones. Shaly or clay-rich interbeds and partings are relatively scarce in the Gull River Formation. The limestones are frequently almost pure, while the dolostones are usually argillaceous and may be silty to very fine sandy.

The three younger Formations, the Bobcaygeon, Verulam, and Lindsay consist of limestones with shaly interbeds and partings or interbeds of limestones rich in argillaceous material. The main lithological difference among these Formations is that the Bobcaygeon Formation contains at least one 20-foot (6.1 m) thick section of almost-pure limestone, whereas the Verulam and Lindsay Formations both contain limestones interbedded or interlaminated with shales or argillaceous limestones. The dolomite content is very low in all three Formations.

Thin section examinations show that, following Folk's classification, lithographic micritic varieties are most frequent in Members A and B of the Gull River Formation, and that pelsparites, biosparites, biopelsparites and intrapelmicrosparites are the most frequent varieties in the other Members and Formations of the Simcoe Group. Fossils are rare in the Gull River Formation, but the other Formations contain beds which are rich in fossils.

Uses for the quarried material depend to a large extent on the lithostratigraphic character, the composition and fabric of the formations occurring in the quarries. The Gull River rocks are generally compact when fresh, especially the limestones. They are used as crushed products but their use as concrete aggregate is somewhat restricted because some beds contain rocks which are alkali reactive in concrete. Such beds are rare, being confined to two submembers only. Their presence must be established by special methods. Petrographic analysis indicates if the rocks in an area or in a quarry are potentially reactive. Alkali reactivity affects the use of the rocks as concrete aggregate only. Special measures must be taken to prevent damage when such material is used in concrete.

The Bobcaygeon Formation contains material which is very satisfactory for concrete aggregate and for other purposes for which a somewhat lower quality material is acceptable. High quality rocks occur in sufficiently thick units in the Bobcaygeon Formation to be quarried profitably.

The Verulam limestones usually contain so many shaly interbeds that sections of rock which will withstand severe exposure or heavy loading are normally not thick enough to permit economic development for crushed rock. The low dolomite content of the rock is an asset, however, for cement production. This is especially true if the Verulam limestones are considered in combination with the overlying Lindsay rocks.

The Lindsay rocks are characterized by a low dolomite content and intense interbedding or interlamination with clayey beds or laminae. This makes these rocks suitable for use as raw material for cement production but unsatisfactory for use as crushed concrete aggregate and probably also for many less demanding uses.

The summary gives only the general characteristics and may not be applicable in specific locations where local variations may have a marked effect on the quality of the rocks.

APPENDIX I

OUTLINE OF FOLK'S CLASSIFICATION OF CARBONATE ROCKS

compiled from

Folk 1959; 1962; 1968; Ham and Pray 1962; Bathurst 1971

Folk's classification deals largely with limestones formed wholly or in part of transported constituents as distinguished from those believed to have been formed by in-place organic growth, and from those carbonate rocks in which recrystallization or other diagenetic and postdiagenetic effects have extensively modified the primary rock features. Folk introduced two principal calcite agglomeration groups which are the building blocks of the limestones, the allochems and the orthochems.

Allochem is an abbreviation of allochemical constituent. It includes "all materials that have formed by chemical or biochemical precipitation *within* the basin of deposition, but which are organized into discrete aggregated bodies and for the most part have suffered some transportation" (Folk 1959).

Orthochems are "essentially normal [chemical] precipitates, formed within the basin of deposition or within the rock itself, and showing little or no evidence of significant transportation" (Folk 1959).

The classification is built around six major elements: the allochems which include intraclasts, pellets, oolites, fossils and fossil fragments; and the orthochems which include the microcrystalline calcite ooze (mud) or micrite, and the coarser-grained, clearer, calcite cement.

Intraclasts are defined as carbonate particles formed by erosion of penecontemporaneous, generally weakly consolidated, carbonate sediment from adjacent sea floor and redeposited by currents. Intraclasts specifically exclude fragments of consolidated limestone derived from emergent land area.

Pellets are generally subspherical aggregations of microcrystalline carbonate material which do not have a distinct internal structure, and which usually show remarkable uniformity in shape and size in a given rock. According to Folk, pellets average from 0.03 to 0.20 mm in size. Particles of similar structure which are larger than 0.20 mm, are classed as intraclasts.

Peloids (McKee and Gutschick 1969 *in* Bathurst 1971, p.84) are formed of cryptocrystalline or microcrystalline allochem aggregations, irrespective of size or origin. This term, which includes intraclasts and pellets composed of micrite or microspar, is very useful especially for the strongly dolomitized limestones in which the size of allochem cannot be distinguished.

Oolites are rounded or oval bodies with a concentric or centripetal structure formed in loci of vigorous and continuous current or wave action in places where calcite is being rapidly precipitated. Their most common size is between 0.1 and 1.0 mm.

The terms *Fossils, Fossil Fragments* or *Skeletal Particles* need no description.

The orthochem *Micrite*, an abbreviation of "microcrystalline calcite ooze", is one of the normal inorganic or organic (algal, bacterial, etc.) precipitates formed within the basin of deposition, which shows little or no evidence of significant transport. It consists of calcite crystals ranging from 1 to 4 μm (0.001 to 0.004 mm) in diameter. Micrite refers to the matrix, the sedimentary material mechanically deposited between the allochems, but it "is just as likely to be an altered marine cement as an altered lime mud" (Bathurst 1974, p.269). "In hand specimen, this is the dull and opaque ultra-fine-grained material that forms the bulk of 'lithographic' limestones . . ." (Folk 1962, p.66). It is difficult to distinguish micrite from silt-sized carbonate particles without thin sections.

The orthochem *Sparry Calcite Cement* is clear calcite, having a grain size no smaller than 4 μm (0.004 mm). It generally forms as a chemically precipitated filling or as neomorphic calcite grains later increasing in size due to recrystallization. The general term *Spar* includes *Microspar*, a crystal mosaic with grain diameter from 4 to 10 μm and even 50 μm (0.004 to 0.050 mm) (Bathurst 1971, p.346). Grains with diameters about 10 to 50 μm (0.01 to 0.05 mm) may be termed *Pseudospar*.

In dividing the carbonate rocks into five types, Folk (1959) places primary emphasis on the relative proportions of allochems and orthochemical constituents.

Type I rocks with a dominance of allochems in sparry calcite cement;

Type II rocks with a dominance of allochems in micrite;

Type III rocks with a dominance of micrite;

Type IV rocks formed of in-place structures, such as reefs, or algal stromatolites (mats);

Type V rocks intensely modified by recrystallization, the later increase in grain size, or by dolomitization, the replacement of calcium carbonate by dolomite.

The rock names are formed by combinations of the roots of names given to the six basic components. The first part of the name refers to the allochem composition (intra-, pel-, bio-, and oo-), and the second part refers to the character of the orthochem material (-micrite and -sparite). The detailed classification is based on numerical values, such as the volumetric proportions of allochems and the average grain size of the constituents. More complete descriptions are made by adding modifying terms, designating the type of fossils or by the use of other suitable modifiers describing aspects such as grain size, admixtures of terrigenous material or replacement material like chert and dolomite. Although the names imply the origin of the limestones, they also signify textural characteristics influencing the qualities of rocks. Assigning names to dolomitized rocks, Folk's rock type V, which are quite widespread in Ontario, is difficult because selective replacement with dolomite frequently obliterates the original texture of the rock.

TABULATED SIZES OF ORTHOCHEMS AND ALLOCHEMS

Table 6 GRAIN-SIZE SCALE FOR CARBONATE ROCKS
Authigenic-Orthochemical Calcite and (or) Dolomite Constituents (Folk 1962, p.74; 1968)

	SIZE IN mm
Extremely coarsely crystalline	Over 4.0
Very coarsely crystalline	1.0 – 4.0
Coarsely crystalline	0.25 – 1.0
Medium crytalline	0.062 – 0.25
Finely crystalline	0.016 – 0.062
Very finely crystalline	0.004 – 0.016
Aphanocrystalline	Under 0.004

Table 7 CLASSIFICATION OF LIMESTONE BY SIZE OF TRANSPORTED CONSTITUENTS (ALLOCHEMS)
(Folk 1962; Hewitt and Vos 1972, p.iv)

Calcirudite A limestone composed of transported fragments predominantly 1 mm and more in diameter (median allochem size is larger than 1.0 mm).

Calcarenite A limestone composed of transported fragments, such as fossil debris, pellets, predominantly from 1 to 0.062 mm in size.

Calcilutite A limestone composed of clay-size and clay- to silt-size carbonate material less than 0.062 mm in size; it results from lithification of calcium carbonate mud.

In general terms, micrites are aphanocrystalline.

Microspars are approximately very finely to finely crystalline. Spars are from very finely to extremely coarsely crystalline.

The most frequent texture of sparite and dolomite is medium crystalline as defined by Folk.

Microcrystalline is used by Folk (1964, p.138) to describe the 1 to 5 μm (0.001 to 0.005 mm) grains forming calcite ooze; or pellets, e.g. "aggregates of microcrystalline calcite"; etc. Microcrystalline is used with the same general meaning in this report. In the same way aphanic is used for megascopic descriptions in the original meaning of the word, *not visible*, without exact connotation to grain size.

Hewitt and Vos (1972), p.iii) use a different crystallinity classification, although several terms are the same or similar such as aphanitic (under 0.2 mm, not detectable with the naked eye); or microcrystalline (0.05 – 0.2 mm, aphanitic with crystals detectable under 10-power hand lens, equivalent to lithographic); or cryptocrystalline (under 0.05 mm, individual crystals only detectable by microscopic examination, equivalent to lithographic).

GLOSSARY OF SELECTED SEDIMENTOLOGICAL TERMS

compiled from

Bathurst 1971, p. 545-548; Folk 1959; American Geological Institute 1972; Hewitt and Vos 1972; Moorhouse 1959; ASTM Designation: C294.

Anhedral Descriptive of the shape of mineral grains on which crystal faces are absent.

Aphanic Said of the texture of carbonate rocks

characterized by individual crystals or clastic grains whose diameters are less than 0.01 mm (Bissell and Chilingar 1967 *in* AGI 1972) or 0.005 mm (Chilingar *et al.* 1967 *in* AGI 1972). Texture in which the crystalline constituents are too small to be distinguished with the unaided eye; used in the text for description of hand specimens.

Argillaceous Clayey or containing appreciable clay material, usually suggesting more than 10 percent by volume of the rock.

Argillaceous Film Argillaceous lamina adherent to carbonate rock fragment after breaking along a stylolite or seam.

Argillaceous Seam Portion of a bed in which the clayey material gradationally increases toward the top of the bed. Usually the top part of a bed containing repeated clayey concentrations parallel to the layering of the rock.

Biomicrite A limestone composed of skeletal, fossil particles in a matrix of micrite.

Biomicrosparite A microsparite containing fossils or fossil fragments.

Biopelmicrite A limestone composed of pellets or peloids (allochems) and skeletal, fossil particles in a matrix more abundant in micrite than sparry calcite cement.

Biopelsparite A limestone composed of pellets or peloids and skeletal, fossil particles in sparry calcite cement.

Biosparite A limestone composed of skeletal, fossil particles in sparry calcite cement.

Biostrome A distinctly bedded and widely extensive or broadly lenticular, blanket-like reef-rock, rarely over 15 feet (4.6 m) thick, built of and composed mainly of remnants of sedentary organisms such as corals, algae, crinoids, etc., enclosed in bedded limestone of different lithologic character.

Cherty Carrying sparse to abundant nodules, lenses or stringers of chert. Fresh chert is a hard, extremely dense or compact siliceous rock composed, in Paleozoic rocks, of silica in the form of finely crystalline to aphanocrystalline quartz and (or) chalcedony.

Coquinoid Characterized by abundant content of fossils, predominantly shells or shell fragments.

Dismicrite A fine-textured limestone, a variety of micrite, containing irregular patches of sparry calcite filling cavities caused by local disturbances such as burrowing organisms or soft sediment deformation. The resulting openings are filled with irregular grains or stringers of sparry calcite with or without pellets or intraclasts.

Euhedral Descriptive of the shape of mineral grains which are characterized by crystal faces.

Fabric The arrangement of crystal grains in a rock in terms of their sizes, shapes, and crystallographic orientation.

Facies Areally segregated parts of differing lithology belonging to any genetically related body of sedimentary deposits.

Geopetal All the widely distributed spatial characters of a fabric that enable us to determine what was the relation of 'top' to 'bottom' at the time the rock was formed (Sander 1951 *in* Bathurst 1971, p.546).

High-Calcium Limestone Limestone that contains less than 3 percent impurities (silica, alumina, iron and other insolubles) and less than 2 percent magnesium carbonate, i.e. less than 4.4 percent dolomite.

High-Purity Dolomite Dolostone that contains less than 3 percent impurities and at least 97 percent combined calcium and magnesium carbonates, i.e. at least 49 percent of the mineral dolomite.

Intraclast Carbonate particle representing a torn-up and reworked, weakly consolidated carbonate sediment; particles larger than 0.20 mm in size.

Intramicrite A limestone composed of intraclasts in a matrix more abundant in micrite than sparry calcite cement.

Intrasparite A limestone composed of intraclasts in a predominantly sparry cement.

Macrofossil Fossil remnant 1 mm or more in length or diameter.

Matrix The sedimentary, mechanically deposited material between allochemical constituents or the material in which larger crystals are embedded; e.g. finely crystalline dolomite rhombohedrons in an aphanocrystalline calcite aggregation.

Micrite Dense, aphanocrystalline rock whose calcite crystals have diameters of less than 4 μm (0.004 mm); may also be termed calcilutite or lithographic limestone.

Micrometre (μm) SI unit of length equal to 0.001 mm; previously called the *micron*.

Microspar A crystal mosaic with grain diameters from 4 to 10 μm and even 50 μm (0.004–0.05 mm) the term 'sublithographic' is frequently used for limestones consisting of microsparry calcite.

Neomorphism An inclusive term suggested by Folk

(1965, p.20-21) for all transformations between one mineral and itself or a polymorph, whether the new crystals are larger or smaller or simply different in shape from the previous ones, or represent a new mineral species; used where it is impossible to distinguish between recrystallization and inversion, or where the mechanism of change is not known.

Oolite Rounded or oval bodies with concentric or centripetal structure having diameters of 0.25 to 2 mm.

Pellet Subspherical allochem aggregations of aphanocrystalline carbonate material less than 0.15–0.20 mm in diameter (AGI 1972), or homogeneous aggregates of microcrystalline calcite, well rounded and sorted, averaging 0.03 to 0.20 mm (Folk 1964, p.139).

Pelmicrite A limestone composed of pellets or peloids in a matrix more abundant in micrite than sparry calcite cement,

Pelsparite A limestone composed of pellets or peloids in a mostly sparry cement.

Peloid Microcrystalline or cryptocrystalline (micritic or microsparry) allochem aggregations irrespective of size or origin (see "Outline of Folk's Classification . . .").

Penecontemporaneous A term which implies that a carbonate agglomeration was formed immediately after deposition but before consolidation of the enclosing rock.

Poikilotopic Descriptive of the fabric of a sedimentary rock in which the mineral grains are of more than one size, and in which larger grains enclose smaller grains or detrital aggregations; e.g. large, usually anhedral, irregular calcite grains enclosing small dolomite rhombohedrons in some dolostones.

Reef A massive limestone built by and composed almost exclusively of the remains of sedentary organisms such as corals, algae, crinoids or bryozoa; developed in places as thick flat sheets (biostromes) or mounds or ridges (bioherms) on the sea floor; usually enclosed in bedded limestone (or dolostone) of different lithology.

Riprap Large angular blocks of quarry stone consisting of specially selected and graded broken rock fragments from about 200 pounds (90 kg) or 1 cubic foot (0.03 m^3), up to 10 to 12 tons in weight. Used for foundations, revetments, protection of slopes and shores or structures exposed to wave action; for dykes, breakwater, etc. The large blocks are usually called "armour stones".

Rubble Angular blocks of quarry stone, irregular pieces of broken rock, from 5 inches (13 cm) to 1 foot (30 cm) in diameter, generally with one smooth rock face.

Shale A fine-grained detrital sedimentary rock formed by the consolidation of clay, silt or mud and characterized by finely stratified structure and (or) fissility that is commonly most conspicuous on weathered surfaces; composed of at least 50 percent clay minerals and detrital silicate minerals from less than 0.004 mm up to 0.0625 mm in grain size.

Shaly Parting Thin fissile laminae or very thin layer of shale between limestone or dolostone beds.

Siltstone A rock having the texture and composition, but lacking the fine lamination or fissility of shale; composed of over 50 percent silt-sized clastic grains from 0.004 to 0.0625 mm in size.

Skeletal Pertaining to material derived from organisms and consisting of the hard parts secreted by the organisms or of the hard material around or within organic tissue.

Spar Clear calcite cement, coarser than 0.004 mm in grain size.

Stromatolite Formed in a shallow water environment under the influence of a mat or assemblage of sediment-binding algae that trap fine detritus and precipitate calcium carbonate.

Stylolite Material on a pressure-solution surface, commonly a film of residual noncarbonate material rich in clay, developed in carbonate rocks. The thin, low to high amplitude, wavy or interdigitate zig-zag clay-rich film may be coloured dark by bituminous matter.

Subhedral Descriptive of shape of mineral grains characterized by partially developed crystal faces.

APPENDIX II

ALKALI-REACTIVE CARBONATE ROCKS

Alkali reactive rocks occur in Ontario in the Gull River Formation of the Middle Ordovician System. Although rare, their detrimental effect on concrete is so spectacular that it has been studied very extensively.

These rocks, as quarried, are generally fresh, dense, and compact and, according to Swenson (1957) who first examined them in detail, have the properties of a physically and chemically sound aggregate except for alkali reactivity. Gull River limestones have been used successfully for many decades as cut building stone in Kingston and elsewhere, although Hewitt (1964b p.26) reported that the microcrystalline variety from the Napanee area, which has been widely used in Kingston, was relatively brittle and tended to crack. The most harmful feature of some Gull River limestone varieties is the volume increase followed by cracking, which occurs during the use of the rock as aggregate in concrete made with high alkali cement, when the concrete is exposed to moist conditions and above normal environmental temperatures. The detrimental volume increase takes place if high alkali cement, containing from 0.60 to 1.25 percent or more alkalis, expressed as sodium oxide, is used, or if excessive alkali enters the concrete from another source. Cracks originate in the carbonate rock aggregate and continue in the cement paste. Typical pattern cracking, misalignment of structural elements and closing of joints due to expansion may occur.

It was found that the main carbonate rocks involved in the alkali-expansion phenomenon are a special type of dolomitic limestone and calcitic dolostone. Alkali reaction starts with the breakdown of dolomite grains as they react with alkali hydroxides from the cement to form magnesium hydroxide (the mineral brucite), and alkali and calcium carbonates. The following equation in which M represents either sodium or potassium illustrates the dedolomization:

$$\underset{\text{Dolomite}}{CaMg(CO_3)_2} + \underset{\text{Alkali Hydroxide}}{2MOH} \rightarrow \underset{\text{Brucite}}{Mg(OH)_2} + \underset{\text{Alkali Carbonate}}{M_2CO_3} + \underset{\text{Calcite}}{CaCO_3}$$

This reaction depletes the rock of dolomite, and enriches the rock in calcite on the surface of particles, along cracks, and along capillaries. The reaction of the alkali carbonates with abundant calcium hydroxide in the hydrated cement paste regenerates the alkali hydroxides (Seligmann 1964).

Because dedolomization does not cause a volume increase (Gillott and Swenson 1969, p.19) explanations for the expansion accompanying the reactivity are complex. Hadley (1964) postulated that expansion involves osmotic pressure. Hansen (1967) stated that the hydration of an anhydrous reaction product produced by alkali attack on the dolomitic constituents, may cause the expansion; and Gillott and Swenson explained that the expansion is mainly caused by secondary expansion of clay constituents in the rock (Gillott 1964; Swenson and Gillott 1967; Gillott and Swenson 1969). The precise nature of the reaction and expansion of some carbonate rocks is still uncertain (Swenson 1972).

Examinations have shown that the reactive rocks usually have specific petrographic properties, in spite of relatively wide ranges in mineral composition. According to ASTM Designation: C294-69 (1973b, p.209):

> The characteristic composition is that in which the carbonate portion consists of substantial amounts of both dolomite and calcite, and the acid-insoluble residue contains a significant amount of clay. The characteristic texture is that in which relatively large crystals of dolomite are scattered in a finer grained matrix of calcite and clay.

Various workers have found that the calcite to dolomite ratio is frequently between 0.67 and 1.5 which corresponds to from 40 to 60 percent calcite or dolomite in the carbonate portion of the rock (e.g. Hadley 1961; Newlon and Sherwood 1962). The results of the author's study of reactive Gull River rocks in Ontario, however, showed that very few rocks, found to be reactive by the cylinder test, have calcite to dolomite ratios in the above range. According to the petrographic examinations, the alkali-reactive rocks contain 5 to 20 percent clay and clay-like material (Swenson 1972, p.35; cf. also Figure 2 which shows a scarcity of rocks having calcite to dolomite ratios between 0.67 and 1.5 in the Pittsburg and Uhthoff quarries). The clay minerals are predominantly illite and subordinately chlorite.

The texture of the alkali reactive rocks is more easily characterized and recognized than the composition. It consists of an aphanocrystalline matrix of calcite and clay minerals, in which dolomite rhombohedrons, typically smaller than 0.1 mm and often smaller than 0.05 mm (Newlon, Sherwood and Ozol 1972), are randomly distributed. Petrographically,

the rocks are partially dolomitized, argillaceous limestones (calcilutite or micrites). Typical reactive rocks of the Gull River Formation are low in porosity and absorption.

To determine whether a carbonate rock was potentially reactive and expansive, Hadley (1961) developed a 'screening' method which was later adopted by the ASTM as standard method Designation: C586. In this test, small rock cylinders 9 mm in diameter and 35 mm in length are immersed in a 1 N sodium hydroxide solution. The increase in length of the cylinders is measured at specific time intervals after immersion. Results obtained by the cylinder method showed that the reactive rocks are interbedded with innocuous, nonexpansive carbonate rocks, that not all portions of the same rock layer are reactive, and that rocks, which have the compositional and textural characteristics given above for reactive rocks, may not be reactive. The test also showed that the rocks vary in the time at which the expansion started, and the rate and extent of expansion. It was found that the start of expansion was significantly delayed in some rare rock varieties which differ in composition and texture from the more usual, early expansion reactive rocks (Dolar-Mantuani 1964; 1971a).

The late-expansion rocks contain from 10 to 20 percent calcite, have a calcite to dolomite ratio from 0.16 to 0.36 and insoluble residues over 20 percent. Quartz, rare feldspar grains, and dolomite rhombohedrons, all similar in size lie in a matrix of microcrystalline dolomite, calcite and clay minerals. The rocks are distinctly impure, calcitic dolostones rich in clay minerals, and they contain silt- to sand-sized terrigenous quartz as significant accessory constituent. They are classed as silty to sandy argillaceous dolostones.

These late-expansion, alkali-reactive carbonate rocks occur in a few beds in rare quarries containing the more common types of reactive limestones described above. It is generally believed that these rocks are not detrimental to concrete because creep and autogenous healing of concrete may accommodate some late-starting volume changes (Gillott and Swenson 1969, p.21).

To prevent unanticipated concrete expansion by alkali-reactive carbonate rocks, it is important to recognize whether a deposit contains such rocks. In addition to the service record in concrete structures in which the concrete, especially the aggregates were examined in detail, three methods are available to establish potentially alkali-reactive rocks:

1. Petrographic examinations,
2. Testing rock cylinders in sodium hydroxide.
3. Testing rocks as coarse aggregate in concrete.

The Virginia research group (Newlon, Sherwood, and Ozol 1972) recommended the petrographic examinations of aphanic carbonate rocks in thin sections or polished sections to establish the presence or absence of even minor areas of characteristic reactive texture making the rock suspect of being alkali reactive. The amount and distribution of typical reactive texture have to be included in the findings (Newlon, Ozol and Sherwood 1972). They emphasize, as did Swenson and Gillott previously, the importance of careful sampling "because of the cohabitation and interbedding of reactive and non-reactive rocks in what are designated as single lithologic units by conventional geologic criteria". It is generally agreed that petrographic examinations are relatively quick and inexpensive, and, coupled with the calcite to dolomite ratios, can give information about numerous, but still manageable samples.

The rock cylinder test shows the amount and type of expansion of the beds represented by the cylinders, and it is useful in the initial assessment of different strata in a quarry (Swenson 1972, p.35). The most reliable test for establishing the reactivity or nonreactivity of carbonate rocks, and for determining the degree of expansion in concrete, is to test the rock in concrete. This method is recommended even though the expansion of the rock cylinders in sodium hydroxide is comparable with the expansion in concrete.

To test the behaviour of carbonate rocks as coarse aggregate in concrete with high alkali cement, the concrete beams are exposed to 100 percent relative humidity at 70°F (21°C), or 100°F (38°C) to accelerate the alkali reaction (CSA Standard A23.2.24). If the concrete has a linear expansion of 0.05 percent or more in 14 weeks of testing, one may conclude that the aggregate contains deleteriously reactive material. For the time being, there is no general agreement on the acceptance limits for expansion, and the limits should be different for concrete for various uses. The limits should also take into account the influence of concrete mixture proportions, environments of service of concrete, and dimensions of structures (Mather and Mather 1974). Rocks that cause 0.05 percent expansion or more are considered excessively reactive, and are not accepted by the Ontario Ministry of Transport and Communication for use as concrete aggregates in highway construction (Smith 1964).

Examinations show that alkali-expansive carbonate rocks in Ontario occur in two submembers from two adjacent members of the Gull River Formation (Liberty 1971, personal communication; see also the section "Previous Work", under "Gull River Formation"). This indicates that the conditions under which

alkali-reactive carbonate rocks are formed are very specific and rarely fulfilled. It is important to remember (1) that alkali-reactive carbonate rocks are rare, (2) that the degree of expansion may vary from an insignificant amount to highly detrimental amounts, (3) that they are deleteriously expansive only when used together with high alkali cement in a moist environment, and (4) that there are corrective measures which prevent excessive expansion of concrete containing alkali reactive rocks. These are:

1. Use low alkali cement, with about 0.40 percent or less of total alkalis expressed as sodium oxide.
2. Avoid exposures to continual humidity. Partial or periodic drying in outside exposure can stop or greatly reduce the reaction (Swenson 1972, p.35).
3. Avoid placing in areas where de-icing salts will be used.
4. Use a smaller particle size but consider the changes in mix proportion.
5. Dilute the alkali reactive rocks with nonreactive aggregates. This is usually done in practice because only a few layers in a quarry are reactive; even so, reactive rocks could be concentrated in some batches of concrete.
6. Use selective quarrying to eliminate the highly reactive beds, if feasible.

It might be necessary to use more than one 'remedy' to avoid expansion of concrete made with strongly alkali-reactive carbonate rock varieties. If the concrete made with aggregates from a quarry known to contain reactive layers still shows excessive expansion in the laboratory test after dilution with nonreactive aggregates or after elimination of highly reactive layers, the rock should not be used, especially in a concrete structure in which moisture cannot be limited.

Examinations by Swenson and Gillott (1961) have shown that unlike the alkali silica reaction, the alkali carbonate rock reaction is not controlled by the use of pozzolans as partial replacement for portland cement (Swenson 1972, p.35).

RIM-DEVELOPING CARBONATE ROCKS

Investigations of carbonate rocks have shown that reactions between carbonate rock aggregates and cement paste are rather normal, and are not always harmful. Certain reactions are considered beneficial because the bond between the rock particle and the cement paste is improved. In addition to the alkali reaction covered above, reactions at the aggregate/cement paste interface are visible as dark rims on the aggregate particles. They are described by Hadley (1964), Sherwood and Newlon (1964), Buck (1969) and others. The formation of rims in concrete aggregates made from Gull River carbonate rocks are mentioned by Gillott (1963, p.772).

APPENDIX III

PROLONGED COPPER NITRATE TEST

A prolonged copper nitrate staining test is used to speed up megascopic identification of mineral constituents and to provide additional information on the quality of carbonate rocks used for concrete aggregate (Dolar-Mantuani 1962; 1966; 1969b). The test is also used in laboratory examinations of ledge rock samples representative of material used for slope protection, etc. The method gives the following information:

1. Differentiation between types of carbonate minerals and rocks; calcite and limestone are stained blue, but dolomite (mineral) and dolostone are only slightly stained.
2. The presence and amount of impurities on the surface of particles or hand specimens can be determined because they remain unstained. This includes impurities such as quartz, feldspar, chert, clayey films and seams, and other accumulations.
3. In sedimentary carbonate rocks, containing significant amounts of clay impurities, various kinds and degrees of damage are produced when an aggregate or hand specimen is immersed in a solution of copper nitrate at room temperature for 16 hours, or overnight.
4. In addition to staining, the test may produce scaling, flaking, splitting, cracking, exfoliation, or disintegration of carbonate rocks containing concentrations of clay minerals.

TESTING PROCEDURE

A 1 N copper nitrate solution is made by dissolving 51 g of hydrated copper nitrate, $Cu(NO_3)_2 \cdot 3H_2O$, in 200 ml of water. After soaking in the nitrate solution, the rock is briefly immersed in strong ammonia solution to stabilize and intensify the blue stain produced on carbonates by the complex copper salts. Finally, the rock is carefully washed in tap water so as not to destroy the characteristic changes which may have occurred during the test. The copper nitrate solution as well as the ammonia solution can be used a number of times, the nitrate solution preferably after being filtered, as long as its normality is not changed significantly, and the ammonia solution as long as it smells strongly of ammonia.

SAMPLES

The test is performed on hand specimens, ledge rock pieces up to 8 inches (20 cm) in length, and on crushed aggregate samples. In aggregate samples, and in gravel and sand containing carbonate particles, the test is conducted on 200 particles of each fraction separately, starting usually with the fraction passing the 1½ inch (38 mm) sieve. The lower limit is set at the No. 50 (0.297 mm) sieve size because particles finer than this are easily lost during the washing, and damage cannot be recognized in very fine particles.

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